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RAILROAD DECISION SUPPORT TOOLS FOR TRACK MAINTENANCE

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DISCLAIMER

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TECHNICAL SUMMARY

Title

Railroad decision support tools for track maintenance

Introduction

North American railroads spend billions of dollars each year on track maintenance. With expenditures of this level, incremental improvements in planning or execution of maintenance projects can result in either substantial savings or the ability to complete more projects. Decision support tools can enhance maintenance planning efficiency and aid new railroad employees in evaluating alternatives while they gain experience. Beyond the practical applications of support tools, the study of how choices are made will provide insights into the decision-making process. This will include a better understanding of the relationships that need to be considered to make decisions that are efficient, effective, and aligned with the organization's strategy.

The primary purpose of this research is to enable objective evaluation of track maintenance options because the most efficient alternative is not always obvious. To do this, the decision-making process and the costs that should be considered must be understood. Without this understanding, we cannot ensure that the tools are consistent with current practice or find ways to improve either decision making or maintenance costing.

Approach and Methodology

The research proposed in this document addresses several aspects of railroad maintenance decision making.

- Chapter 2 describes an integrated framework for track maintenance planning that incorporates all aspects of the planning process over a network.
- Chapter 3 discusses a methodology for determining the cost of train delay, which will enhance the understanding of how track maintenance and other service disruptions will impact train operations.
- Chapter 4 discusses a way to select the optimal track components or maintenance procedures to ensure that the track can operate at the lowest cost.
- Chapter 5 discusses the effects of aggregating maintenance activities on elongated maintenance windows.

Findings

One way to improve how track maintenance is planned is to integrate the process of predicting, evaluating, and scheduling maintenance for all track components. This must include evaluation of indirect costs, such as train delay and accidents, in addition to direct costs. Coordinating maintenance of the different track components will allow for more efficient maintenance planning and execution, while ensuring that the most effective method of maintaining the track is selected.

Conclusions

Track maintenance decision support tools have the potential to help the railroads perform maintenance more efficiently, thereby permitting more effective use of the same budget or reducing maintenance expenditures. They can also guide new employees by helping accelerate development of their knowledge and experience.

Recommendations

Improving the railroad's ability to perform effectively will allow them to better serve customers and the public. Additionally, researchers can benefit from the general relationships and procedures uncovered and developed in association with this work such as how accident rate correlates with the time from maintenance, train type and delay accumulation, and the most influential factors in track ownership.

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PRELIMINARY REPORT

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List of acronyms used

AAR	Association of American Railroads
AREMA	American Railway Engineering and Maintenance-of-Way Association
ARTC	Australian Rail Track Corporation
B/C	Benefit-cost
CBA	Cost-benefit analysis
DCF	Direct cash flows
EPA	United States Environmental Protection Agency
FRA	Federal Railroad Administration
IAROR	International Association of Railway Operations Research
IHHA	International Heavy Haul Association
INFORMS	Institute for Operations Research and Management Science
IRR	Internal rate of return
LCC	Life-Cycle Cost
NPV	Net present value
RSAC	Federal Railroad Administration Railroad Safety Advisory Committee
RTA	Railway Tie Association
STB	Surface Transportation Board
TEMS	Transportation Economics & Management Systems
TMSP	Track maintenance scheduling problem
USDOT	United States Department of Transportation
VTI	Vehicle-track interaction

Chapter 1. Introduction

North American railroads spend billions of dollars each year on track maintenance. With expenditures of this level, incremental improvements in planning or execution of maintenance projects can result in either substantial savings or the ability to complete more projects. Decision support tools can enhance maintenance planning efficiency and aid new railroad employees in evaluating alternatives while they gain experience. In either case, objective and analytical methods have been shown to improve management decisions (Davenport & Harris, 2007). Beyond the practical applications of support tools, the study of how choices are made will provide insights into the decision-making process. This will include a better understanding of the relationships that need to be considered to make decisions that are efficient, effective, and aligned with the organization's strategy.

The primary purpose of the research I am pursuing is to enable objective evaluation of track maintenance options because the most efficient alternative is not always obvious. To do this, the decision-making process and the costs that should be considered must be understood. Without this understanding, we cannot ensure that the tools are consistent with current practice or find ways to improve either decision making or maintenance costing. Maintenance personnel can use the decision support tools' recommendations and apply their qualitative knowledge of the system to make a final determination. Specific applications of these questions are discussed in subsequent chapters.

This research also advances the theoretical understanding of how maintenance decisions affect the total cost of track ownership and operation. A better understanding of how train delay is accumulated will clarify the relationship between traffic disruptions, such as maintenance and accidents, and train operations. This relationship will allow for better theoretical analyses of how to minimize the effects of traffic disruptions. Additional insight into the relationship between track quality and accident risk will enhance our appreciation of how changing maintenance schedules will affect safety on a section of track, which may influence how maintenance thresholds are determined and how to study the total cost of track ownership. Overall, having a better understanding of how management decisions affect costs will guide how information is gathered and inform how future research will investigate maintenance effects.

The costs of track maintenance can be divided into two categories: direct and indirect. Direct costs are incurred as a result of performing maintenance, such as equipment, material, and labor. Direct costs are typically tracked to some extent by the railroads and can be determined on a per unit basis. These costs are regularly considered in maintenance analysis because they are readily available; however, indirect costs are not always considered because they are harder to quantify.

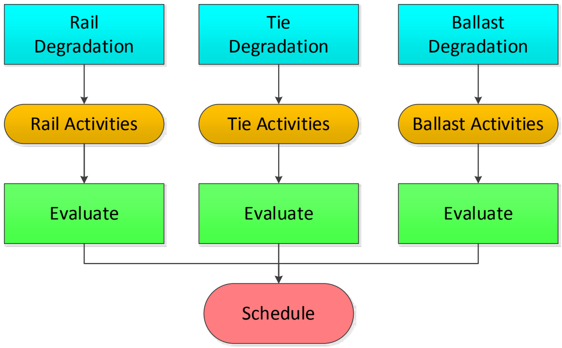
Indirect costs are secondary influences of either performing or deferring maintenance. In my research, indirect costs consist of train delay impacts and disruption risk. Train delay can be further divided into line delay and network effects, although these are not always treated separately. Line delay only considers the line that is disrupted, while network effects are from other parts of the network, including other lines and rail yards. Methods for determining line delay are discussed further in Chapter 3. Disruption risk is the expected cost of disruptions, e.g. accidents or slow orders, based on given track and operating conditions. The relationship between track maintenance and accident risk is not well understood, but methods for considering this cost are discussed in later chapters. It is expected that maintenance will reduce the occurrence of unplanned service disruptions, which could be taken as benefits of track maintenance. Operational benefits may also accrue due to an improved track condition although sufficient data are not currently available to consider this aspect.

The research proposed in this document addresses several aspects of railroad maintenance decision making. Chapter 2 describes an integrated framework for track maintenance planning that incorporates all aspects of the planning process over a network. This will enable maintenance planners to better evaluate all aspects of the track system and select the most cost-effective method of improving the track. Chapter 3 discusses a methodology for determining the cost of train delay, which will enhance the understanding of how track maintenance and other service disruptions will impact train operations. This will allow for improved objective maintenance plans that incorporate all aspects of railroad operations. Chapter 4 discusses a way to select the optimal track components or maintenance procedures to ensure that the track can operate at the lowest cost. This analysis identified some key costs inputs and decisions, which can aid in improved analysis and data gathering. Chapter 5 discusses the effects of aggregating maintenance activities on elongated maintenance windows. Understanding these consequences and when they are incurred allows for improved planning using this relatively new maintenance scheduling methodology.

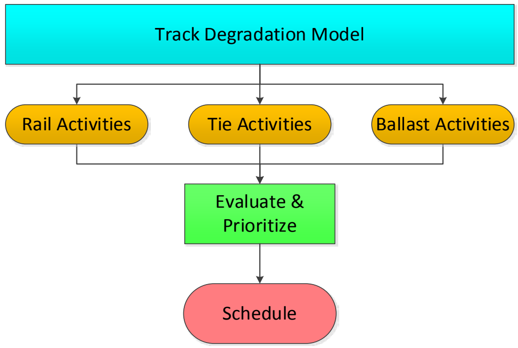
Chapter 2. Integrated Model for Evaluation and Planning of Railroad Track Maintenance

The track maintenance planning process has historically been treated as distinct steps with each track component managed separately (Figure 2.1(a)). Different levels of management evaluate each step for each major element of the track system, e.g. rail, ties, and ballast, and maintenance may be performed on a particular component because funds are available even if another type of maintenance may be more effective at improving the overall track condition. This method does not allow for track maintenance to be optimized globally. The framework proposed here combines the maintenance planning steps in a new way to optimize the final result, which will lead to more cost-effective maintenance decisions (Figure 2.1(b)).

The three general steps in track maintenance planning are track evaluation, project selection, and project scheduling. Track evaluation is the process of determining when future maintenance needs to be performed. This may include degradation models, projections based on trend data, established intervals, rules of thumb, or simply the intuition and experience of maintenance personnel. Project selection consists of determining when and where maintenance should be performed based on the track condition. Logistics and scheduling can be optimized once projects have been selected.



(a)



(b)

Figure 2.1(a): Traditional maintenance planning, (b) proposed maintenance planning framework

One of the benefits of the proposed work is to show how maintenance planning can be improved by using a more comprehensive approach. Understanding how maintenance activities improve track condition provides a better perspective of the most efficient way to accomplish that goal. By putting economic values to operational disturbances, maintenance planners can better understand when to perform maintenance to minimize the total cost of track ownership and operation.

2.1 Overview of the state-of-the-art

Varying levels of research have been conducted on the steps in the maintenance planning process, but it does not appear to have been examined comprehensively. Track evaluation, specifically degradation modeling, has traditionally been studied in component-specific models without consideration for other aspects of the track structure (Wells, 1982; Reiner & Staplin, 1983; Davis, 1987; Davis & Gudiness, 1987; Chrismer, 1988; Martland & Auzmendi, 1990; Acharya, 1994; Kumar, 2006; Garnham et al., 2007; Qian et al., 2014; Walton-Macaulay et al., 2014). Although understanding individual component performance is essential for a foundational understanding of how the track performs, track components do not exist in isolation (Hay, 1982). A comprehensive track degradation model will allow for consideration of component interactions, which will give a more accurate understanding of how track degrades and improve maintenance planners' ability to plan accordingly (Ferreira & Murray, 1997; Zhang et al., 1997; Zhang et al., 2000).

Additionally, the model would ideally be developed from a mechanistic and empirical basis to better account for variable operating conditions. Many industries have shifted to mechanistic-empirical modeling including pharmaceuticals, chemical reactors, and highway design

(Yamashita & Hashida, 2003; Duarte et al., 2004; Roesler & Hiller, 2013). Specifically, AASHTO's Pavement ME software analyzes the mechanistic aspects of pavement degradation based on the expected loading while considering behavior variation (Roesler & Hiller, 2013). Similar methods can be applied to the track structure since there is inherent variability in the life of the track components. Although some failure mechanisms are fairly well understood, further investigation is needed to determine the factors that cause them (see Lamson & Dowdall, 1985; Cannon & Pradier, 1996; Indraratna et al., 1998; Cannon et al., 2003; da Silva et al., 2003; Zeman et al., 2009).

Data to develop degradation models can come from a variety of sources, including both manual and automated inspections. Most railroads use data from track geometry and rail defect inspection vehicles, and at least one railroad uses high-speed cameras with machine vision to monitor track conditions (Clouse et al., 2006; Sawadisavi et al., 2008; Carr et al., 2009; Wanek-Libman, 2012; Wanek-Libman, 2014). These provide information that can be directly linked to track components for maintenance evaluation. Some railroads have started using VTI equipped rolling stock to monitor track conditions (Hicks & Stevens, 2009; Clark et al., 2015; Cowie et al., 2015; Crump et al., 2015). These measurements can be used for predicting when track maintenance should be performed, but they may not be as helpful in determining what maintenance activities would best improve the track condition. If this could be overcome, VTI measurement data could be a viable source of data for degradation modeling due to the near continuous monitoring they provide.

To predict when to perform maintenance, track condition data needs to be applied to a statistical model or distribution. The Weibull distribution has commonly been used to model component degradation and failure rates, including all major components of the track structure

(MacLean, 1957; Orringer, 1990; Shyr & Ben-Akiva, 1996; Lim et al., 2004; Kumar, 2006; Jeong & Gordon, 2009). The Weibull distribution is also advantageous due to its simplicity because it only has two parameters that need to be calibrated. The shape factor determines how sinusoidal the distribution is, and the scale factor is based on the average failure interval and determines distribution width. Other distributions may be considered to ensure that the Weibull is the best fit for track degradation modeling. As more advanced models are developed or adapted, the Weibull model can be augmented or replaced.

Once local maintenance personnel evaluate their subdivision's needs, track maintenance projects are recommended to successive levels of management who prioritize which projects should be completed. Capital and renewal maintenance is then determined by senior engineering managers who distribute the rail, tie, and surfacing budgets according to a variety of subjective and objective criteria. The limited research published on this topic in the rail sector has focused on the use of degradation models to determine when to conduct maintenance, rather than on project selection. There has been research on related elements in other areas. For example, in highway infrastructure maintenance planning, research has been done on optimizing what maintenance should be performed and when, but it does not appear that work has been published on optimizing the maintenance of multiple components (Ouyang & Madanat, 2004; Ouyang, 2007; Gu et al., 2012). Factory maintenance research has considered the effect of multiple components and will be discussed in Chapter 5.

In general, project selection uses various economic principles and rules. Two common methodologies that are used in investment decisions are NPV and IRR; however these, especially IRR, rely on having positive revenues to determine if a project is satisfactory (Ross et al., 2013). NPV has a long history of use in the railroad industry since it was pioneered by Arthur

Wellington in the late 1800’s to evaluate how timing influences revenues and investments (Dulman, 1989). It can be applied to maintenance planning by minimizing overall costs. Care needs to be taken to consider the fact that not performing maintenance has increasing expenses in the form of potentially higher accident rates and slow orders. Ignoring these degradation effects is a common mistake when considering investment decisions in the information technology field, where delaying investment will result in impaired operations and increasingly negative cash flows. Christensen et al. (2008) term this the “DCF Trap,” and could be avoided by considering the increased disruption risk associated with not maintaining the track.

Another method that is increasingly being used in transportation project evaluation is the CBA, which evaluates the costs and benefits to determine the relative appeal of a given project. The output is commonly reported as the B/C ratio. CBA is commonly used when determining the impact of social projects, where the benefit is derived from a reduction in future costs (Andersson et al., 2004; Bryan et al., 2007; Vatn, 2008; ARTC, 2010; Landau et al., 2015). However, as all costs incurred will be experienced by the railroad, cost minimization would accomplish the same goal in a simpler manner.

Once the maintenance activities have been identified and evaluated, the most cost-effective set of projects should be selected. The knapsack model is one of the most common methods for selecting activities from a given set. With this model, projects are chosen to maximize benefits while constraining the cost and time requirements (Alanne, 2004; Kellerer et al., 2004; Gabriel et al., 2006). In the rail industry, the knapsack model has been used to select capacity improvement projects (Lai, 2008).

For project selection, the metrics listed above (NPV, B/C ratio, or total costs) could be optimized to ensure that the most effective projects are being selected. If overall costs are minimized, direct and indirect costs of all selected projects, including unplanned service disruptions, would need to be considered. A budgeting constraint would only consider direct costs since indirect ones are not typically accounted for in the maintenance budget. The cost of mobilizing maintenance equipment would also not be considered here because it will vary based on how the projects are scheduled and would be evaluated in the activity scheduling step.

Once the optimal project mix has been selected, they must be scheduled to ensure the most effective implementation. The TMSP model as developed by Peng et al. (2011) is one that has potentially beneficial characteristics. This model was specifically designed for the rail industry and minimizes transportation costs while considering the effects of work windows, activity sequencing, and linear project clustering for a preselected set of projects. It would be important to ensure that the scheduling model does not duplicate the other modules, e.g. considering aggregation of maintenance or work window length. While this does not appear to be a problem with Peng et al.'s TMSP, it is something that should be considered, and may result in a simpler optimization model. Previous attempts to address railroad maintenance scheduling have considered minimization of train disruptions (Higgins, 1998; Higgins et al., 1999), minimization of maintenance costs including set-up and take-down times (Lake et al., 2002), consideration of job prioritization (Budai et al., 2006), and balancing the impacts of maintenance and when the activity needs to be completed (Cheung et al., 1999). Peng et al. (2011) improve on other large scale TMSP models by considering travel costs and exact consideration of network distances.

2.2 Summary of technical approach and research results

Previous findings on this topic have been presented at the Joint Rail Conference, World Congress on Railway Research, AREMA Annual Conference, and the INFORMS Annual Meeting, all occurring in 2013. These conference proceeding papers provide additional details and are included in Appendices A, B, and C.

A preliminary proof-of-concept version of the model considers the track as a whole rather than individual components. The track condition was assumed to degrade over time as represented by an increase in accident rate following a Weibull distribution. Direct maintenance costs and durations were assumed to increase proportionally with the accident rate. Each track segment started with a different condition in year zero and were classified as Good, Poor, or Priority (Figure 2.2). These classifications are not directly correlated with FRA track class standards but are determined by maintenance personnel as ways to rank track degradation severity.

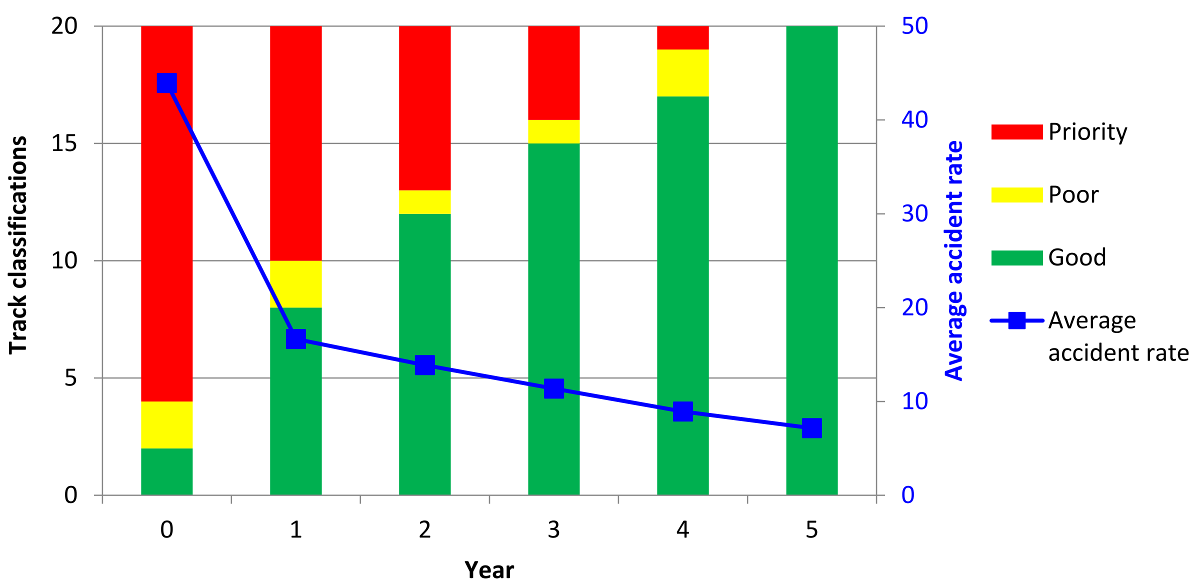


Figure 2.2: Year-end track exceptions and average condition

Projects were selected to maximize the sum of B/C ratios. Benefits consist of the accident risk reduction over the next year, and costs include both direct and indirect, such as residual accident risk and train delay. Refer to Chapter 1 for further discussion of direct and indirect costs. Project selection was constrained by the budget and available time to work during the year. The case study was a linear route and maintenance was performed on the selected segments from one end of the route to the other, so a complex logistics model was not required.

Although renewing Priority track segments provide the most benefit, they may not be selected because the higher costs will decrease the B/C ratio or the cost is too high given the remaining budget. If Priority segments are not selected, ordinary maintenance is performed. Poor track segments are selected for renewal with any remaining budget after the Priority segments with the highest B/C ratios have been selected. If a Poor segment has conditions that would increase the consequence of an accident, e.g. hazardous materials or passenger traffic, then the B/C ratio may increase to a level where it would be selected over a Priority segment. Good track segments should not be maintained because doing so would result in unnecessary disruption of the track structure and operations. Poor segments that are not maintained and Good track segments will evolve into Priority and Poor segments, respectively. Future developments could adapt track measurements to allow for consideration of FRA and internal maintenance limits.

Lovett et al. (2013) developed a mathematical model to look at the selection of maintenance for a single component in a single year. This resulted in preference for low-cost solutions at the expense of projects with higher benefits, which could be resolved using the cost minimization method described above. This removes the prioritization that the B/C ratio provides, but minimizing the overall costs, including accident and operation expenses, would create the same effect.

2.3 Intellectual merit and expected impact

While there has been extensive research into track evaluation and the logistics of track maintenance, relatively little has been done in the area of project evaluation and selection, which is where this research will focus and can provide the greatest benefit. This research will be a new application of optimization techniques to track maintenance activity selection. In the rail industry, this research will aid in integrating condition evaluation, project selection, and logistics into a unified decision analysis tool. This comprehensive approach will improve maintenance planning by considering the total cost of track ownership and operation. It will also provide a better understanding of the tradeoffs between proactive and reactive maintenance, which can influence management decisions in maintenance thresholds and deferrals. Additionally, the modified knapsack problem that considers prioritization criteria will be a novel variation of the problem and a contribution to the optimization field.

2.4 Remaining challenges and goals

The remaining challenges in this work consist of improving the representation of the planning steps in the model. As mentioned in Section 2.2, a cost minimization model may be more effective and straightforward than maximizing the B/C ratio. Since the benefits are simply reductions in cost, minimizing the cost should have the same effect as maximizing the B/C ratio but in a simpler form by removing the non-linearity. This could be configured as a mixed integer mathematical program similar to the rail maintenance model developed by Lovett et al. (2013), but expanded to include multiple track components. Penalty costs can also be applied to Priority track segments that are not maintained to reflect ordinary maintenance costs and potential slow orders. Gathering validation data, specifically for maintenance costs and practices, will help ensure that the model is accurately portraying railroad operations.

A related problem that will need to be resolved before this framework can be fully applied is identification or development of improved track degradation models. Advanced maintenance planning is not possible without these models because maintenance planners would not be able to accurately determine the track's future condition. This may be beyond the scope of this research, and railroads may have proprietary models that could be used.

A key aspect of developing maintenance planning models is understanding what type of action will most effectively correct the condition, and when it should be performed. Research needs to evaluate the relationship between particular aspects of track condition, accident occurrence and cause, and other performance parameters. Liu et al. (2016) have studied the relationship between accident rate and various operating conditions, including annual gross tonnage, method of operation, and track class that can be used for preliminary modeling. While this is a useful starting point for determining how the accident rate changes with track condition, it is confounded by the fact that routes with higher tonnage and track class typically receive more maintenance. This extra maintenance would result in higher quality track, and, therefore, lower accident rates (Liu et al., 2016). This proxy needs further investigation to increase its usefulness in determining the optimal time to perform track maintenance.

2.5 Plan for completion and success criteria

This project can be completed within the next year because the foundational work is complete. Additionally, it is closely related to Chapters 4 and 5, so additional work required here can be accomplished more efficiently. The scope was intentionally limited to focus on the activity selection to ensure it will provide the most benefit and be completed in a reasonable timeframe. If time permits, improved degradation models and accident rate relationships could be further explored.

This research can be considered a success when the model selects maintenance activities that result in reduced overall track operation costs while providing a cost estimate that experienced railroad personnel find reasonable. The model should be able to do this while interacting with degradation and logistics models.

Chapter 3. Determining Freight Train Delay Costs on North American Railroad Lines

Various stakeholders are affected by freight train performance, including railroads, shippers, and the public. In North America, railroad companies own the track, operate the freight trains, and consider the costs of delayed trains internally. This differs from European railroads where delay penalty costs are often negotiated explicitly in the contracts between train operating companies and rail infrastructure owners (Gibson et al., 2002). Beyond the cost to railroads, shippers are affected by both the declining value of goods and the expense of holding inventory. The public directly experiences externalities due to emissions and grade crossing delays, as well as potentially higher prices as a result of the impacts to shipper and railroad operations. Since these costs are not explicitly incurred by the railroad, they may not be considered when evaluating the costs and benefits of maintenance and infrastructure improvements.

3.1 Overview of the state-of-the-art

There have been a number of attempts to determine the delay costs to railroads. The earliest mention of train delay cost I have found dates from the beginning of the 20^{th} century and was one dollar per train-minute payable by the contractor responsible for the delay (Committee No. I. - On Roadway, 1904). More recent values range from $200 to over $1,000. Each of these estimates used different assumptions, which accounts for the range of values.

Smith et al. (1990) considered aggregate equipment and lading costs for several train types. One weakness of these values is that they are dated, and advances in technology and lading rates would make them inaccurate for modern usage. While investigating the consequences of positive train control, the RSAC (1999) provided a value for freight train delay but did not provide any rationale. More detail was provided for passenger train delay costs, but only the cost to passengers was included as opposed to train operation and ownership costs. Lai (2008) has limitations similar to the RSAC freight train delay cost in that a cost is provided without a definite data source. Lai (2008) does list the kinds of costs that would be included, namely: "(1) unproductive locomotive cost; (2) idling fuel cost; (3) car/equipment cost; and (4) crew cost."

Schafer and Barkan (2008) went into more detail by using industry data to consider locomotive, railcar, fuel, and crew costs. This approximation does not incorporate lading and only considers cars owned by the railroad, thereby omitting car-hire costs and the opportunity cost of lost freight revenues. Schlake et al. (2011) proportionately adjusted the Schafer and Barkan value for application to a different train length. This shows the importance of establishing a framework for determining train delay costs because delay costs will vary based on train type and composition. Dingler (2010) examined the effect of train delay on capital costs and fleet size requirements and expanded on Schafer and Barkan's estimation by including the costs of all cars, locomotives, crews, and lading for both bulk and intermodal trains. Fuel costs were estimated from rail simulations, and other values were based on published industry sources. It should be noted that lading costs will only be incurred if the delay results in the cancelation of shipments, meaning that it should only be considered to the extent that delays diminish capacity or improvements expand it (Dingler, 2010).

Due to the difference in how the various historical train delay costs were determined, it is difficult to compare them or identify which value is better for a given circumstance. This is also a concern since hourly delay costs should be applied differently based on train operations. Another limitation of the previous studies is that the authors did not evaluate how other stakeholders were affected by delay, the exception being the RSAC study for passenger trains. Some publicly funded projects are required to identify the associated costs and benefits, which may include the effects of train delay on other stakeholders, but the guidance is limited when it comes to specific applications (USDOT, 2014).

Shipper impacts caused by transportation delays and delivery variation have been analyzed for general business situations, but not specifically in the context of rail. Shippers will primarily be affected by inventory devaluations and holding costs. All goods have a useful life, and the longer those goods are in transit, the less of that life is available to the end consumer. This reduction in useful life can be taken as a cost to the shipper because it will sell for less or will not provide the same value as if the good had arrived on time. This is less of a concern for bulk commodities or raw materials where the primary loss in value is that its use is delayed, compared to perishable or manufactured goods, which may expire or become obsolete. Previous research has identified the approximate amount goods will devalue each day, which is also known as the daily discount rate (Winston and Shirley, 2004). Holding costs consists of taxes, insurance, maintenance, obsolescence, and warehousing (Simchi-Levi et al., 2008). They are frequently approximated at 25% of the value of the good, but the actual amount will vary by industry and location (Stock & Lambert, 2001). Lead time variation affects holding costs because it will increase the uncertainty that the goods will be in stock when they are needed for either sale or use. The increased uncertainty will require a larger buffer inventory, known as safety stock, to avoid stockouts. Typically, only demand variability is considered when determining inventory levels, but the same principle can be applied to lead time, which would directly affect when the goods are available (Schroeder et al., 2011).

Since the public is not directly party to freight shipments, train delay effects are negative externalities of railroad operations. Two that specifically affect the public are pollution and grade crossing occupation. The Office of Regulatory Analysis and Evaluation (2012) of the USDOT has determined the cost of emissions based on their effect on health, property value, and climate change. These can be adjusted to hourly rates based on the locomotive fuel economy, emissions, and operations (EPA, 1998; Frey & Graver, 2012; USDOT, 2014). Grade crossing delay occurs because a train is either traveling at a lower speed or is stopped on the line. The value of travel time has been evaluated by the USDOT for various roadway users and can be applied to specific circumstances (Ayala, 2014), but how to apply these costs to train delay does not appear to have been explored.

As mentioned above, the existing work on train delay does not consider the effects of different train type operations. One important factor is time spent in yards and terminals. Manifest trains have the most complex yard operations because they are made up of cars coming from and going to a variety of destinations. They are routed between classification yards where cars from various arriving trains are sorted and assigned to departing trains bound for the same subsequent yard. Delays on the line will reduce the likelihood that a locomotive or car will be in the yard when its connecting train leaves. Tykulsker (1981) has referred to the probability that a railcar or locomotive makes its connection as its PMAKE, which is affected by the yard availability time, or “avail”, and the yard efficiency. An efficient yard can have a shorter avail that results in a PMAKE of one (Tykulsker, 1981), but this reduces the available buffer time while increasing the probability that a delayed railcar or locomotive will miss its connection.

Another factor that should be evaluated is mode shift. This is primarily a concern with intermodal trains due to the value and priority of the lading. Hwang (2014) did an extensive literature review and found that none of the existing mode choice models include the cost of petroleum, which was a dominant factor in transportation mode choice decisions (TEMS, Inc., 2008). While Hwang's model does not explicitly handle travel time, the model can be adapted to consider this aspect.

3.2 Summary of technical approach and research results

This work was presented at the 2015 IAROR Conference on Railway Operations Modelling and Analysis.

Different train operating scenarios will result in differences in how delay cost components accumulate. Three common types of train operations are unit, manifest, and intermodal. Unit trains perform similarly to a conveyor belt because they repeatedly carry a single type of good between the same origin and destination. While unit trains typically do not depart until they are fully loaded, I represent their departures with average intervals to meet a given level of service. The trainsets remain connected and do not stop at yards for additional marshalling. As mentioned above, manifest trains stop at yards where railcars are sorted into new trains going to other yards. Intermodal trains have characteristics similar to both unit and manifest trains as a set of intermodal cars are kept together to travel between two intermodal facilities. Since intermodal cars usually remain in origin and destination terminals for a longer time, the locomotives are transferred to other trains. If containers on an intermodal train are going to different destinations, the cars remain together, and the containers are removed and resorted (Rickett, 2013).

Since unit trains stay as a set of railcars and locomotives in dedicated service, they represent a lumpy cost. The timing of the investment will depend on the route length and delivery interval. The operating cost per cycle increases linearly until a point where the railroad must purchase additional rolling stock, after which the previous slope resumes (Figure 3.1).

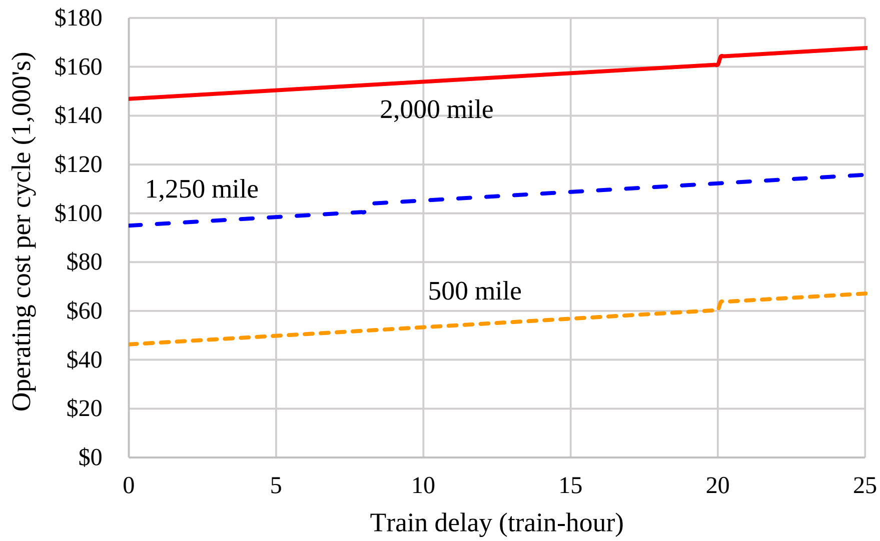


Figure 3.1: Variation of operating cost with respect to delay and route length

Manifest train delay is primarily complicated by marshalling yards. Yard operations are designed to provide a buffer to ensure connections (Figure 3.2). In this case, railcars have a yard availability of six hours, but at least two hours are required to assemble the train. After four hours the delay cost becomes constant because the railcar will not be able to make its connection and will have to wait until the next train departs and arriving slightly earlier or later will not affect when it leaves the yard. A similar effect is observed with locomotives, but with a shorter yard availability.

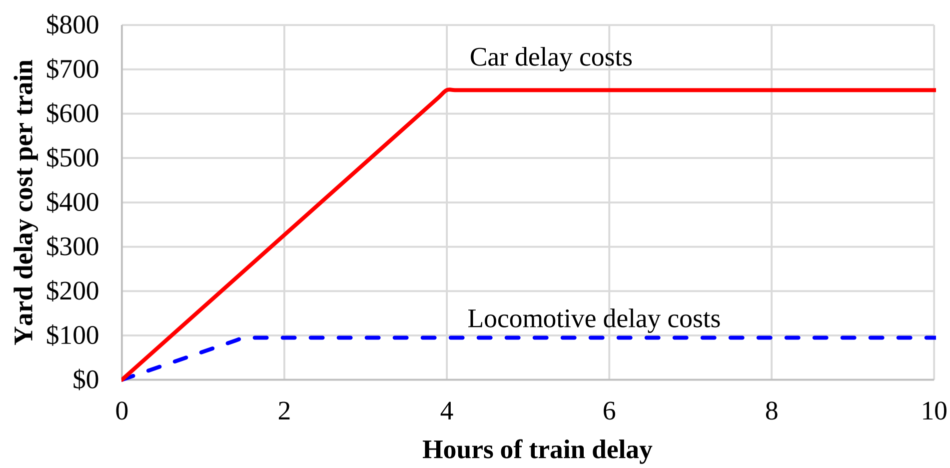


Figure 3.2: Yard delay cost accumulation

Most intermodal train delay costs will be calculated in the same way as the other two train types including the necessary number of trainsets and buffer time in the yard. Due to the high priority and value of intermodal lading, additional delay increases the likelihood of mode shift to trucks. A modified version of the freight mode choice model developed by Hwang (2014) was used to determine how much freight would be shifted from rail to truck based on the amount of delay. The modification consisted of having the same initial rail and truck travel distance, which was increased proportionally so the rail travel time at the longer distance will equal the base travel time plus the additional train delay.

The shipper and public costs are not as central to maintenance planning, so they will not be addressed in detail here. As long as the lading shipping time, or lead time, is consistent, the only shipper delay cost will be the lading devaluation. These costs tend to be quite low based on the values found in the literature (Winston & Shirley, 2004). As mentioned above, increased lead time variability results in the need for additional safety stock, and higher holding costs, because the shipper does not know when the new shipment will arrive. For grade crossings, the effect of delay on the public will be dependent on the number of crossings affected and the length of the route. As delay accumulates, it will reduce the average train speed on the line and increase the amount of time that each crossing is likely to be occupied. The distribution of crossings and how each is affected needs to be considered including the fact that trains may stop in between crossings. In the latter case, only delays that directly affect the crossings should be considered. Emissions depend on how the trains are operated, but the average operation can be used to approximate the effect of a single train. As more delay is accumulated in the system, more trainsets will be on the line, so there will be greater overall level of pollution at a given point in time.

This chapter shows the impact of train delay on railroads, shippers, and the public for different train types. Each train type requires unique applications of each of the delay cost components. It also shows that an average delay cost may not effectively represent the incremental delay experienced everywhere along the spectrum. For example, the length of the route will affect grade crossing delay costs, and lumpy rolling stock investments will result in higher costs for particular ranges of delay. Additionally, some costs are affected by delay variability rather than the average value such as shipper holding costs. This shows that delay must be considered in specific applications to effectively evaluate the associated costs.

3.3 Intellectual merit and expected impact

While there have been a number of attempts to determine train delay costs, few of them provide the resources to determine train delay for different operating scenarios, and only one of them considers the consequences to another stakeholder. This work provides a more flexible way to evaluate these costs for all stakeholders. As the understanding of how train delay influences the various stakeholders improves, the operational impacts of track maintenance, meet and pass delays, and accidents can be better quantified and accounted for when planning is done for either maintenance or capacity upgrades. It will also provide a better understanding of how improvements will benefit the different stakeholders allowing for a more equitable distribution of costs. Part of this analysis has also examined probabilistic yard effects, which can improve understanding of how a train is affected by delay given that some of the delay may be absorbed by the planned yard dwell. Beyond the applied benefits of more detailed delay costing, this will also enhance the theoretical analysis of railroad operations because it allows for better quantification of indirect consequences of traffic disruption.

3.4 Remaining challenges and goals

Further refinements to the methodology will be made to prepare these findings for publication in *Transportation Research Part B: Methodological*. The remaining problems for this effort are in the areas of yard delays, an improved mode split model, and the effect of delay variation on shipper costs. The yard delay is currently handled by assuming that there is only one departure to each destination per day. While this is frequently the case, the ability to consider multiple departures each day will allow increased flexibility in determining yard influences.

Since the selected mode split model does not explicitly consider the consequences of delays, efforts will be made to identify ways to either modify, supplement, or replace the model. The current method may not adequately consider the impact of delays since rail transportation typically benefits from longer hauls. Further research into mode split models will be conducted to determine if a more applicable one is available. This may be especially true given the decline in petroleum prices.

The handling of shipper delay costs can also be improved to consider the effect of delivery variability. Since the model only uses average train delays, the holding costs are not currently estimated. Looking at the variability of delay due to either yard buffer or infrastructure levels will give additional insight into how these costs are affected but may be outside the scope of this work.

3.5 Plan for completion and success criteria

Since the current formulation is largely complete, updating the yard delay implementation, evaluation of alternative mode split models, and preparing the paper for publication can be completed within the next year. The delay variability can be evaluated for further development as time permits. The success of this analysis will be based on the ability of the model to determine the costs associated with delay to the affected stakeholders in a manner acceptable to railroad operating personnel.

Chapter 4. Comparison of Railroad Track Maintenance and Upgrade Options

To efficiently keep track in proper working order, maintenance personnel must identify the components and maintenance activities that will accomplish this most cost-effectively. A general model for objectively determining this for a wide range of alternatives does not appear to have been previously published. Such a model would help maintenance planners understand the impact of possible decisions and improve the efficacy of the track design and maintenance. Determining how to maintain railroad track is similar to the process used in factory maintenance, where various options are compared, and the most cost-effective option is selected (Levitt, 1996). For railroad track, the cost of a particular maintenance option includes the direct costs of the activity, plus indirect costs due to the associated train delay, accidents and slow orders, and degradation of other components. To effectively compare alternatives, an extended time period must be evaluated to fully realize and potentially differentiate their effects. In this chapter, I will describe an LCC model with the above characteristics applied to crosstie type comparisons.

4.1 Overview of the state of the art

Component and maintenance activity alternatives can be compared using an LCC analysis. A specific application of the component and maintenance practice comparison methodology is the comparison of concrete and timber ties, which are the two most common crossties in North America (RTA, 2015). A tie-type comparison is a good starting point due to the nature of the maintenance and the amount of existing research on the topic. Ties are simpler to model because they are discretely replaceable components as opposed to rails or ballast that can be maintained *in situ*, making them harder to quantify. Some previous research has been done on crosstie type comparisons, but the authors admit that they did not adequately consider maintenance differences between the two tie types, nor does it appear they included the effect on accident rates (RTA, 2006; Zarembski & Kondapalli, 2007).

As mentioned in Chapter 1, both direct and indirect costs must be considered when making a cost comparison. Some direct cost information is tracked by Class I railroads. Maintenance personnel’s ability to effectively analyze decisions is directly related to their access to accurate data. If such information is available, then unit costs for material and labor can be used, but equipment costs require a more in-depth methodology (Burns, 1989). If material and equipment costs are unavailable, approximations based on industry data may be usable. For general modeling, labor costs can be approximated using industry or government sources (STB, 2012b; AAR, 2012a, 2012b), but materials and equipment costs are less accessible. Materials may be purchased under contract and equipment costs will vary based on what equipment is used and how it is operated and maintained. For the tie-type comparison values determined by the RTA are used. These include the costs of labor, equipment, and materials, which simplifies the cost determination.

Indirect costs rely on more complex interactions than direct costs and are not always sufficiently examined despite having a significant impact on the outcome of a maintenance alternative comparison (Zarembski & Gauntt, 1997; Simson et al., 2000; Patra et al., 2009). Delay costs are one indirect cost that is immediately apparent when doing track work. These can consist of delays on the line affected by maintenance or other delays that occur throughout the network because of the disruption. There are a number of factors that affect these expenses (discussed in more detail in Chapter 3).

If indirect costs can be reduced through maintenance, the difference can be treated as a benefit. Accidents, slow orders, and certain other track maintenance costs are examples of this. The risk of an accident can be calculated as its probability or rate of occurrence multiplied by the average cost (Liu et al., 2011). Accident costs will vary based on the cause, infrastructure features and operating conditions such as track class, annual tonnage, and signaling system (Liu et al., 2016). Some component types, specifically ties, appear to correlate with changes in accident rates as well, although there may be other confounding factors. Further investigation into the causes of accident rate reduction, such as higher levels of maintenance, will be required before accurate relationships can be developed. Costs associated with hazardous materials releases, lost lading, litigation, and other costs are not included in the FRA (2011) Accident/Incident Database. Therefore, accidents costs are likely to have a greater impact than is shown in this study.

Slow orders refer to reduced speed limits placed on sections of track due to various temporary track conditions (AREMA, 2012a). Although they do not cause the same level of disruptions as accidents, they still reduce service quality. Initial analysis indicates that slow orders have a relatively insignificant cost, although they reduce line capacity. The influence of slow orders on capacity will need to be investigated further because industry personnel indicate that their costs are more substantial than indicated by my initial findings.

As mentioned in Chapter 2, the condition of each component potentially affects the others. AAR research has found that tie condition affects the costs of tamping but not rail replacement (Elkaim et al., 1983); however, recent questions about the influence of support conditions on broken rails may warrant additional study in this area. There may be other degradation effects based on the condition of the various track components, which require further study and may lead to additional cost considerations.

Comparison between two types of components or procedures is most effectively made in an LCC analysis, which can perform comparisons of this kind (Brown & Yanuck, 1985; Flanagan et al., 1989). A general railway infrastructure LCC model was developed by Zoetmann (2004), and an application of this model was applied to rail and ballast maintenance (Andrade, 2008). A shortcoming of this model is that it does not consider accidents, which can contribute a substantial cost over the life of a track component. This may be because the model was developed in Europe where track-caused accidents are relatively infrequent.

4.2 Summary of technical approach and research results

A specific application of this work was presented at the 2015 Annual Meeting of the Transportation Research Board and recently published. The model was applied to a heavy-axle load line with timber ties in which continued use of timber ties was compared to replacement with concrete ties. A sensitivity analysis was also performed to determine which inputs have the greatest impact on the preferred crosstie material.

Figures 4.1 and 4.2 were developed by running the LCC model over 45 years for timber and concrete cross ties on four existing timber crosstie rail lines with different traffic and infrastructure levels. The timber tie alternative assumes regular renewals and the concrete tie alternative assumes out of face replacement every 45 years. The results are presented in two different ways, cost category (Figure 4.1) and cost type (Figure 4.2). For most lines, timber ties result in higher LCCs, which is largely due to surfacing and train delay. As previously mentioned, slow order costs appear negligible, but this may be due to insufficient consideration

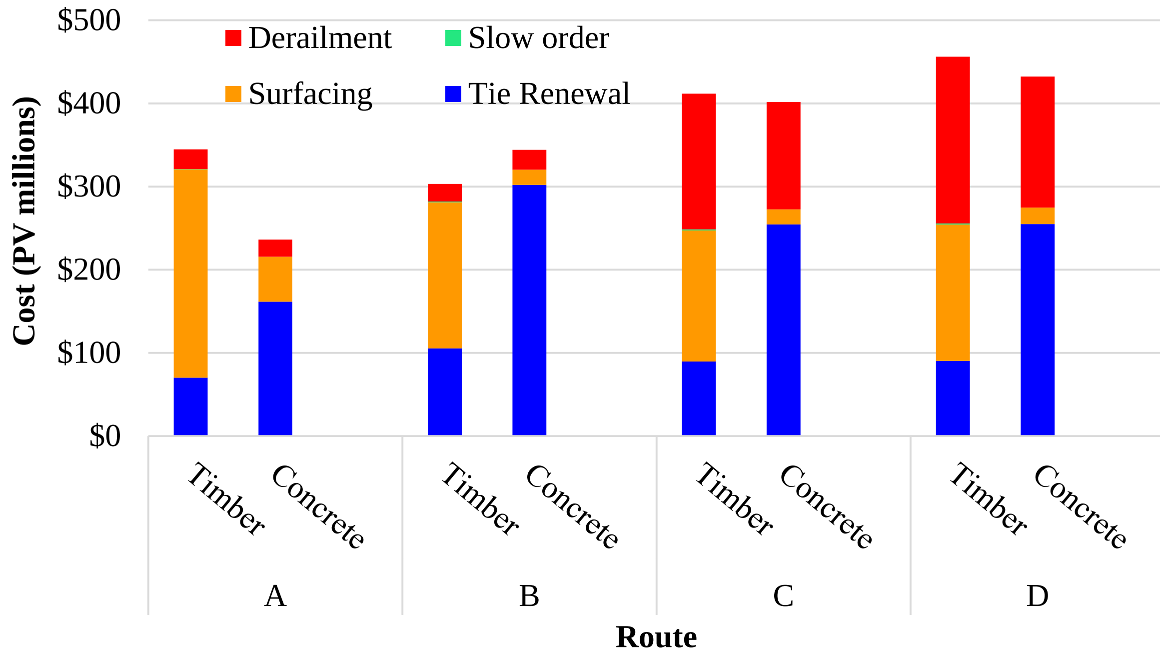


Figure 4.1: Case study results divided by cost category.

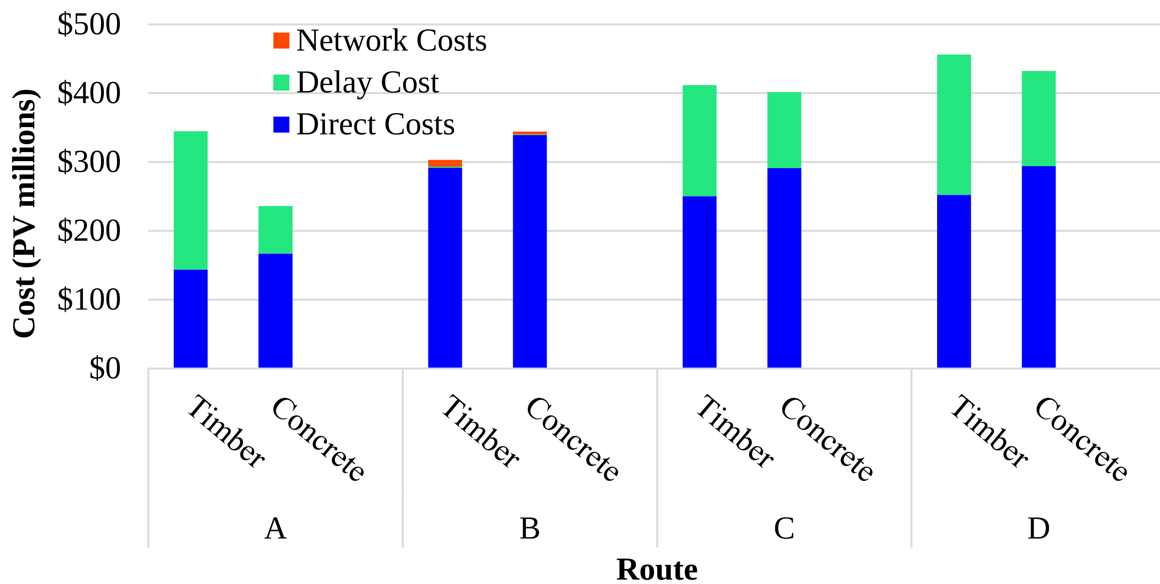


Figure 4.2: Case study results divided by cost type.

of network effects. The impact of delay costs can also be discerned, which are more than half of the cost of the timber tie track, thereby underscoring the importance of including the cost of delay in maintenance planning. Network costs are only shown for line B because line C, the other route with a detour available, has sufficient capacity to continue operating at a reasonable level even when a track segment is taken out of service for maintenance.

A sensitivity analysis was performed on the LCC model to determine which inputs had the greatest influence on the model outcomes. Several variables were analyzed considering track, operating, and disruption characteristics. All of the variables were tested in two scenarios, with and without alternate routes available.

Figure 4.3 provides a more concise comparison between the five most sensitive variables for each alternative. In both cases, the same set of five variables were the most sensitive: concrete tie costs, timber tie renewal speed, concrete tie spacing, timber tamping frequency, and the discount rate, although they differed in magnitude and relative importance. The concrete tie costs were of particular interest because of practitioner statements that the RTA concrete tie costs were too high. This variable ranked as the most sensitive for both scenarios, which underscores the importance of accurate tie cost data. Timber tie renewal speed will affect the delay costs, which can contribute a large amount of the total cost (Figure 4.2). Tamping frequency will affect the secondary costs, which are substantial for timber crosstie lines (Figure 4.1). Tie renewal speed will vary based on the number of ties replaced and tie condition (Burns, 1989). Tamping frequency will also vary greatly based on the traffic and the nature of the sub-structure.

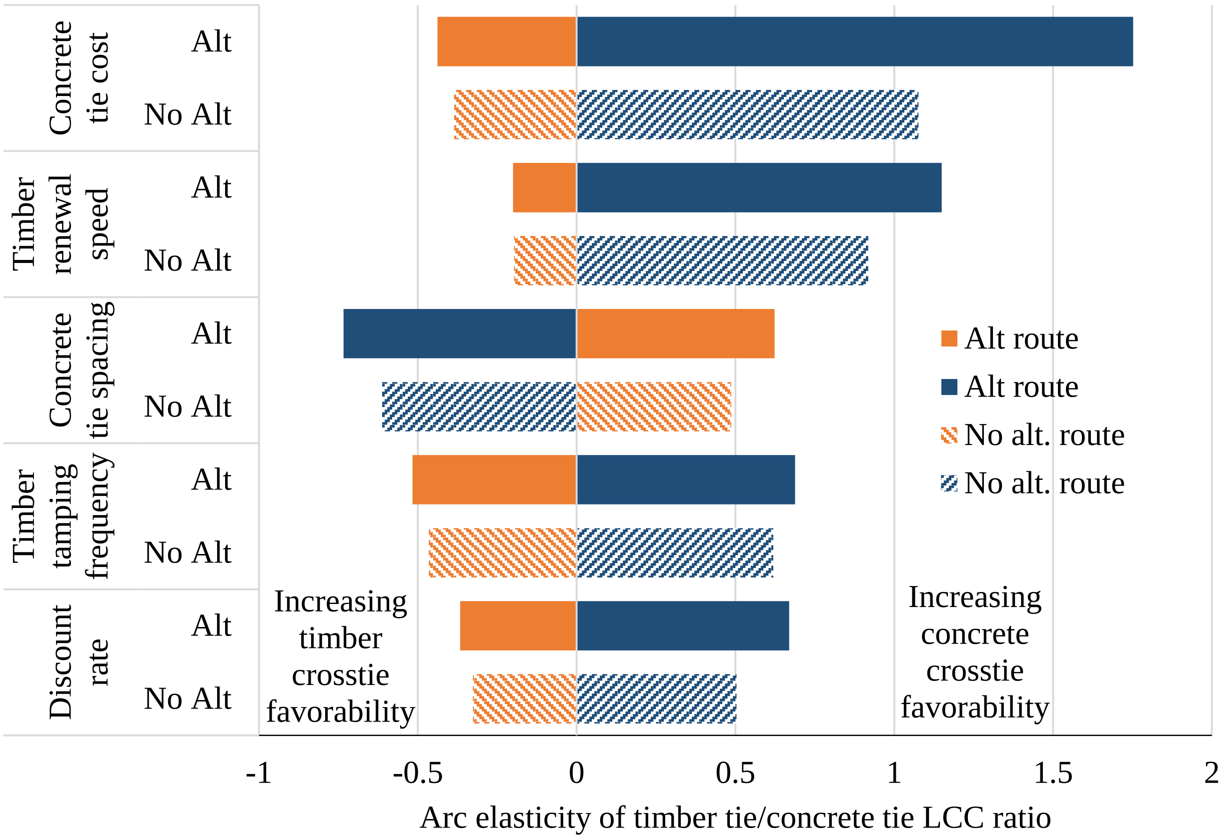


Figure 4.3: Sensitivity analysis results for the five most sensitive inputs.

Concrete tie spacing is determined by track engineering personnel and is typically set at 24 inches, but may be between 20 and 30 inches (Hay, 1982; AREMA, 2012b). If engineering rationale can be found to change the spacing, it could have a substantial impact on the overall cost. The primary reason that concrete tie spacing has such a large influence on the comparison between concrete and timber ties is that it affects the number of ties that will need to be installed. Since concrete ties are assumed to all be installed in the first year of the analysis, their entire cost for replacement is considered as an undiscounted cost.

The discount rate is directly related to the effect of tie spacing as well as other costs. Higher discount rates favor maintenance performed in small amounts over a long period, such as timber tie replacements, while lower discount rates favor maintenance activities conducted earlier in the period. This is because higher discount rates reduce the impact of costs incurred later in the analysis period (Dimson, 1989; Brealey et al., 2007). Internal discount rates are primarily a business decision based on the cost of borrowing capital and expected rates of returns to investors and can be highly variable. For financial analysis, the cost of capital, which is reported by the railroads to the STB (2012), is synonymous with the discount rate (Brealey et al., 2007; Ross et al., 2013).

4.3 Intellectual merit and expected impact

This research will provide a better theoretical understanding of how different cost categories affect the total cost of track ownership and operation. In practical application and theoretical research, knowing the influence of specific costs can help ensure that information is gathered in the most cost effective manner. At the same time, it brings awareness that data must be collected on some inputs even though their impacts are not directly apparent. Specific advances in this work are the inclusion of accident and slow order risk, which have not previously been considered. Although slow order costs are not substantial in this analysis, they may warrant further investigation to ensure that they are properly accounted for. Knowing the influence of these events can also drive improvements in routine data gathering which will enable more accurate future analysis.

This work may also lead to the development of a mathematical model that can be used to optimize the placement of advanced components over a line, subdivision, or larger network. Although this has not been explored in detail, it has the potential to advance the theoretical understanding of how costs interact over the network. This will have specific impacts on local decision-making processes, and will improve how future research on track maintenance decision making is performed.

4.4 Remaining problems and goals

Further investigation is needed to develop this analysis. Specifically, validation data should be gathered on the costs of track maintenance. This will improve understanding of the effect on tie maintenance, as well as the indirect costs of maintenance on other track components. Further multivariate analysis needs to be performed to determine if and how accident rates vary with different tie types. This will provide insight regarding possible benefits from premium track components. Although there do not appear to be any published data on the failure of concrete ties before their 40-50 year life, such failures have occurred a number of times and have impacts on both intermediate replacement and slow order costs. Further information may be available from the RailTEC infrastructure team.

Beyond improving crosstie costing methodology, it would also be beneficial to determine how these principles can be applied to other track components and maintenance practices. This could be accomplished with a mathematical model, which would represent the associated direct and indirect costs for any given railroad track based maintenance or upgrade comparison. Since the framework is complete for the crosstie comparison, expanding the methodology for other maintenance practices could be completed relatively quickly.

The previous model was coded in Excel using VBA, which will probably continue to be used. If an optimization model is required for future development, it will likely be a mixed integer program. Further expansion of the accident and tie-type specific failure rates will require the use of probabilistic models and regression analysis although this is beyond the scope of this research.

4.5 Plan for completion and success criteria

This analysis has already resulted in a journal publication. Further improvements may be made in conjunction with the work in other chapters, which would be completed in accordance to those timelines. This model will be deemed a success when it can determine the LCC of maintenance or component alternatives in a manner that is consistent with railroad’s empirical data and seems reasonable to rail industry experts.

Chapter 5. Aggregation of Maintenance Activities on Extended Work Windows

Over the past two decades, North American railroads have begun aggregating maintenance activities on extended work windows. Industry professionals indicate that a form of this practice has been in use in Europe for much longer. This method involves removing a line from service for several days and performing maintenance on multiple parts of the track system. CSX and BNSF have been performing maintenance jamborees or blitzes since 1999 (Dischinger, 1999; Railway Track & Structures, 2015), and Union Pacific was using elongated work windows as early as 1996 (Ingles, 1996). This differs from more traditional maintenance practices where track is taken out of service for a few hours at a time to allow maintenance on specific track components, e.g. rail grinding, tie replacement, or tamping. This approach allows traffic to keep flowing, but it reduces maintenance efficiency because crews spend considerable time waiting for trains to pass, then setting up equipment only to have to remove it again before the work window ends. Conversely, extended track outages are more disruptive to train operations because of additional costs associated with substantially delaying, rerouting, or canceling trains (Burns & Franke, 2005b).

5.1 Overview of the state-of-the-art

Previous research has analyzed various aspects of maintenance aggregation. Burns & Franke (2005a, 2005b) quantified the efficiency of longer work windows; however, they assumed all aspects of the track would be maintained rather than analyzing specific combinations of individual activities and the possible resultant efficiencies. Burns and Franke provide considerable detail in the time and costs required to perform the individual maintenance activities carried out on the track, which can be applied to this and other analysis. Other research has considered aggregating maintenance on lines that are out of service because shipper traffic has been temporarily suspended, so operational interruptions are not a factor (Martland, 2008; Peng, 2011). There are also other railroad-specific models for traditional maintenance planning (see Higgins, 1998; Higgins et al., 1999; Peng et al., 2011 as examples).

More research has been performed in the factory domain and in other systems that have high downtime costs, which are similar to the railroad in many respects. Cho and Parlar (1991) reviewed several models for maintaining “multi-unit systems.” One model they evaluated specifically looked at systems where failure of a single component would cause the entire system to shut down. In the context of railroad track, a “component” failure that prevents trains from running would generally be the failure of several component units, such as a group of ties. This is due to redundancies in the track structure but would have the same effect. Another model Cho and Parlar (1991) discuss evaluates the impact of maintaining components out of cycle because the system has already been shut down to work on another component. This can be directly applied to track that must be taken out of service for maintenance.

Maillart and Fang (2006) developed a model that includes both availability of the system and maintenance cost. Their model evaluates units in series rather than in parallel, which would be the case when analyzing a series of railroad track sections rather than components in a given track section. Considering units in a series would be beneficial when evaluating combinations of similar track maintenance activities on adjacent track segments rather than combining different types of maintenance at the same location. The model developed by Yao et al. (2004) corresponds particularly well with the maintenance aggregation situation. It includes the higher cost of unplanned downtime, modification of a general maintenance schedule to correspond with other maintenance, and lost production. Component ages can be determined by the calendar or operations cycles, which is analogous to most railroad components where age may be measured in years or gross tonnage.

Wildeman et al. (1997) evaluated grouping maintenance activities that have the same setup cost. Setup costs are defined to include both actual setup costs and the costs of taking the system out of service. For track maintenance, this could be a reasonable assumption when evaluating train delay costs, which will be the same on a train-hour basis regardless of the activity. In contrast, the actual costs to set up the equipment will not be the same and will still need to be considered if multiple maintenance activities are performed at the same time. Another aspect of this model that could be beneficial for application in railroad track maintenance are the penalty functions that are applied to activities shifted from the optimal schedule. These penalty costs are associated with degradation of the system, so it is possible that they will be negative if the maintenance is done early. This penalty cost could be analogous to accident costs, which could be determined for a given operating condition.

Elements of these models can be used to develop a railroad-specific maintenance aggregation optimization model. For the preliminary analysis, a model that adjusts an existing traditional schedule was used to demonstrate the effects of aggregated maintenance on elongated work windows.

Wildeman et al. (1997) also discuss the benefits of combining activities associated with reducing duplicated efforts, but there will be other effects if the schedule is adjusted. Specifically, in the case of railroad track maintenance, tamping, fastener removal, and flaggers are needed for multiple activities and could be used less frequently if aggregated. Maintenance such as tamping and rail grinding can shorten the component’s useful life if done prematurely, so that should also be considered if sufficient data are available. Aggregating track maintenance activities will also decrease the amount of track time required because work can be overlapped and longer work windows will reduce the number of equipment setups required.

5.2 Summary of technical approach and research results

A model was developed to represent the costs of maintenance aggregation. The model calculates the NPV of the direct costs, savings from aggregation, train delay cost, and accident risk for a given maintenance schedule. This analysis was presented at the 2015 IHHA Conference and the 2015 INFORMS Annual Meeting. It will also be presented at the 2016 Joint Rail Conference. Further work will prepare this research for publication in the *Journal of Transportation Engineering*.

The model was applied to a case study with a 50-year planning period under several maintenance schedule adjustment strategies. Including using a traditional schedule, elongated windows with traditional planning, aggregating maintenance that is already scheduled for the same year, and adjusting the schedule for activities that fall within a three-year aggregation period. For the last scenario, three situations were analyzed, all activities that fall within the aggregation period were scheduled for the first year, the middle year, or the last year in the period. Analyzing multiple strategies allows general trends to be observed.

The evaluation criteria have similar challenges to those discussed in Chapter 4, but the deferral of maintenance that may occur when aggregating poses an additional problem. Christensen et al. (2008) term this “the DCF Trap,” which was briefly mentioned in Chapter 2, but has an even greater impact here. The DCF trap deals with the fact that most DCF and NPV

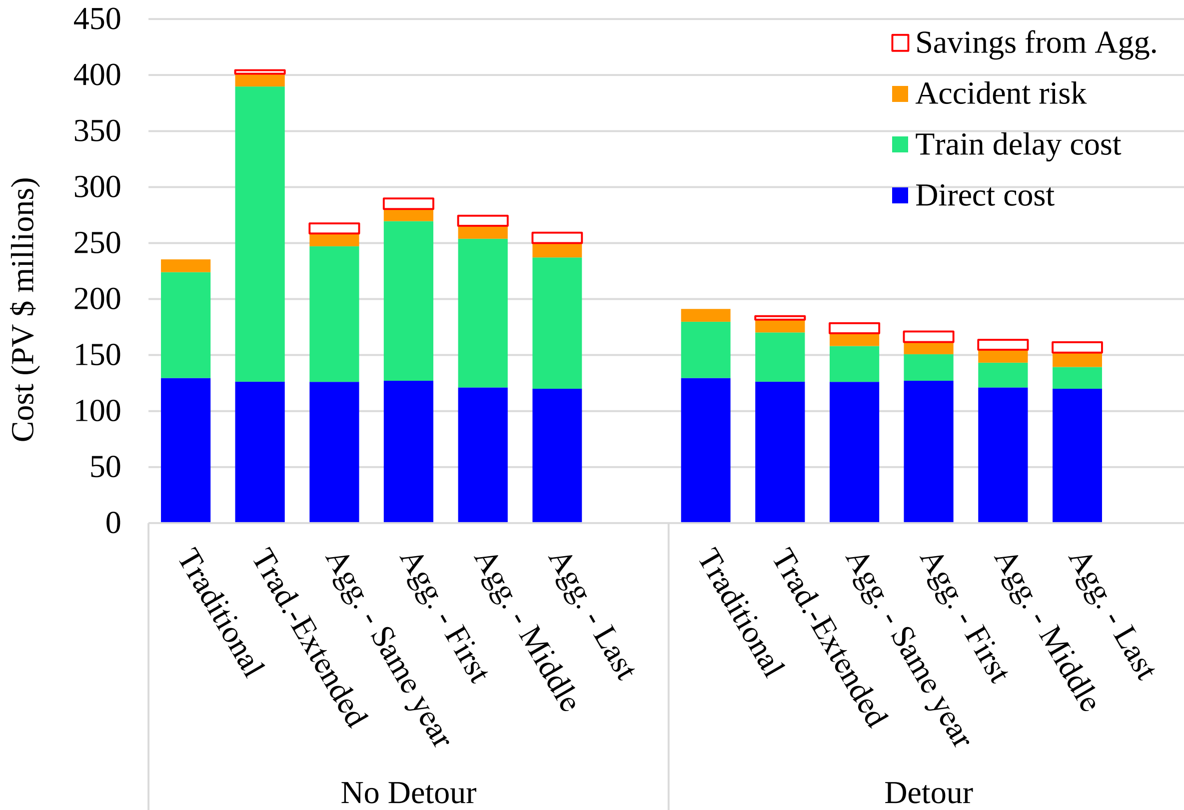


Figure 5.1. Net present value of 50-year LCC discounted at 11%

analyses assume that doing nothing will result in cash flows not changing, despite the fact that delaying investments in upgrades or maintenance will generally result in increased costs. This is why considering accident and other disruption costs are even more important because they represent the increasing costs of not maintaining the track.

Based on the results of the case study, maintenance aggregation with extended work windows is only cost effective if a detour is available (Figure 5.1). If a detour is not available, then the operational disruption is too severe. If a detour is available, the costs decrease with increasing levels of aggregation and elongation. This is because the work is being done more efficiently while allowing traffic to flow. The best comparisons can be drawn between traditional, traditional-extended, and same year aggregation, as only the level of aggregation and window elongation, not the year of completion, is changing. Window elongation has a small cost reduction, but introducing aggregation results in noticeable savings, even if the redundancy savings do not represent a large proportion of the total costs. This is confounded somewhat by the fact that the same year aggregation does not apply extended windows to all maintenance activities, but further analysis can produce a better understanding of what factors reduce costs.

5.3 Intellectual merit and expected impact

This appears to be the first time that track maintenance aggregation has been evaluated from a total cost perspective. The application of principles from manufacturing maintenance to the rail industry allows for improvements in the methodology of how maintenance is analyzed and scheduled. Specific results of this work are the development of a method to quantify the relationship between track degradation on accident risk. This will improve the understanding of costs associated with deferring maintenance, which will be another factor that can be considered when researching maintenance planning. Conversely, observing the effects of performing maintenance early will also help in the theoretical evaluation of when to perform preventative maintenance. Understanding the impact of disruption costs will also increase the incentive to gather accurate disruption data for future analysis. In general, seeing the relative costs of different forms of maintenance aggregation can help both academics and practitioners see how maintenance decisions affect overall costs.

5.4 Remaining challenges and goals

This work will continue by expanding the applicability of the model to better represent actual operating conditions and development for planning and optimization. The primary focus for improving applicability is to include the cost of spot maintenance and slow orders, which will allow for more comprehensive costing of the maintenance schedule. While I do not currently have access to railroad data on slow orders or spot maintenance costs, I am developing models based on publicly available data. These models will determine expected time to a slow order based on track conditions and when maintenance was last performed. Alemazkoor et al. (2015) evaluated the probability of an FRA defect a given amount of time after a lower level defect was detected. Their work could be extended to determine the probability of an FRA defect, i.e. implementation of a slow order, for a given amount of time after maintenance. While the direct costs of slow orders appear to be minimal, I am looking into how to evaluate the network effects of slow orders to determine their magnitude. Once the framework for consideration of these costs has been developed, railroads can substitute their models.

The accident rate model will also be updated to provide more accurate representation of track degradation. While improving the models that determine accident rate based on operating conditions is outside the scope of this work, I will improve their application within my framework. This will likely include using a non-linear equation to represent the track class to accident rate relationship. As I will not be updating the relationships themselves, I do not need additional data to work in this step beyond the time it takes a component to degrade, which will be based on the expected time to slow order that is already being developed. Some statistical tools may be necessary to determine if the non-linear relationships provide sufficient benefit to justify the added complexity, but the specific tools have not been identified yet. If specific railroads have accident rate models, they should be able to substitute them for the general ones I am developing.

An optimization model would allow the cost model to be applied to maintenance planning to take advantage of the benefits of aggregation and elongated work windows. The optimization will use a mixed integer program to determine the least cost schedule. The time value of money calculations will require a non-linear model, but it should be solvable with a standard solver. The one factory maintenance model that mentions solvers states that the model is within the capabilities of most commercial solvers. If the complexity becomes too great, a more novel process, such as a genetic algorithm, might be required, but I have experience developing these. Initial development of the optimization model would evaluate a single track segment. The model could be expanded to a larger network to consider resource constraints, but this could not be performed with a standard solver, and is closer to the work discussed in Chapter 2.

5.5 Plan for completion and success criteria

While the foundational work for this research is already complete, more remains to be done than in the other research areas. Despite this, the work should still be complete within the next two years because the necessary work has already begun. This research will be deemed a success when the mathematical model works in such a way that it schedules maintenance in a realistic manner according to railroad personnel without major human intervention after the inputs have been entered.

Chapter 6. Conclusion

Track maintenance decision support tools have the potential to help the railroads perform maintenance more efficiently, thereby permitting more effective use of the same budget or reducing maintenance expenditures. They can also guide new employees by helping accelerate development of their knowledge and experience. Additionally, the study of how to make effective decisions can provide insight into the relationships that affect them.

One way to improve how track maintenance is planned is to integrate the process of predicting, evaluating, and scheduling maintenance for all track components. This must include evaluation of indirect costs, such as train delay and accidents, in addition to direct costs. Coordinating maintenance of the different track components will allow for more efficient maintenance planning and execution, while ensuring that the most effective method of maintaining the track is selected.

One of the largest indirect costs is train delay, which does not appear to have been adequately considered in previous analyses. Train delay affects all parties involved in train operations, including railroads, shippers, and the public. The component costs to each stakeholder accumulate differently depending on the operating situation, which affects how they are quantified. Without a thorough understanding of the cost of train delay to all of these parties, it is not possible to understand how stakeholders are affected. These values can also aid in identifying potential savings through delay reduction strategies, determining late fees, and how improvement costs should be allocated.

While accident and other disruption costs do not make up a majority of the cost to own and operate the track, safety is a key aspect of any railroad’s strategy. Not considering how track maintenance affects safety prevents decisions from adequately conforming to the railroad's mission. Additionally, considering disruption costs has the potential to change the balance of which maintenance alternative is most cost-effective and should be investigated further.

To ensure that the most effective maintenance activities or components are being used in a given area, there must be a way to compare the alternatives. This is best done from an LCC perspective since it allows for the long-term impacts to be observed and considered. Currently, there is no general method to do this, nor one that includes delay and disruption costs, which affect the total cost of track ownership and operation. Evaluating all costs affected by decisions will also allow maintenance personnel to see how a given component or maintenance practice will change operations and costs. Additionally, the sensitivity of the inputs should be acknowledged to ensure that excess time and money is not expended gathering data that will not have a significant impact on the outcome. This was seen in the tie type comparison, where a few inputs had a greater impact on the relative cost effectiveness of the different tie types than others.

Beyond what maintenance to do, maintenance planners must also determine how and when to perform it. One consideration is if the benefits of performing multiple activities together during extended work windows are sufficient to justify adjusting an individual component's optimal maintenance schedule. A model capable of evaluating the effects of aggregating maintenance over extended work windows can provide track maintenance personnel a resource to justify longer work windows based on their impact on the entire operating environment.

Using models such as those described in this document, railroad personnel can make better objective decisions for track maintenance. This can be beneficial for railroad employees no matter what their experience level because the most cost effective action is not always clear.

Improving the railroad's ability to perform effectively will allow them to better serve customers and the public. Additionally, researchers can benefit from the general relationships and procedures uncovered and developed in association with this work such as how accident rate correlates with the time from maintenance, train type and delay accumulation, and the most influential factors in track ownership.

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