



Predicting the occurrence and cost of temporary speed restrictions on North American freight lines

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ABSTRACT: Temporary speed restrictions, or slow orders, are a major concern of North American heavy-haul freight railroads because they reduce capacity and increase costs. Current quantitative understanding of predicting the occurrence and cost of slow orders is insufficient for consideration in track maintenance planning. This paper discusses a method for determining expected costs for slow orders related to each of the three major track components (rail, sleepers, and ballast) using probabilistic models, direct and delay costs, and assumed maintenance schedules. Slow order costs vary greatly between the three track components due to both the slow order duration and occurrence rate. The quantified change in slow order costs due to changes in maintenance schedules illustrates how the maintenance planning process can consider these effects.

1 INTRODUCTION

Average train speed as reported by the major North American railroads is a key metric of network fluidity (Association of American Railroads 2016). Lower average train speeds increase the number of crews, locomotives, and railcars required to move a given volume of freight during a set period, as well as increasing other associated operating costs (Lovett et al. 2015a). Given the impact of slowing trains, it is not surprising that temporary speed restrictions, or “slow orders,” are a strategic concern for North American heavy-haul railroads; however, it is difficult to isolate the costs specific to slow orders. There are few instances in the literature that attempt to quantify the expected impact, or risk, of slow orders or other disruptions. In particular, Lovett et al. (2015b) found that slow orders related to timber crossties (sleepers) do not have sufficient impact on railroad operations to materially influence track maintenance and operating decisions. This lack of quantitative support for industry practice indicated that further research was required to determine how slow orders affect network operations. One way to estimate future impacts is through risk analysis, which considers both the probability, or frequency, and the impact of an event (Ang & Tang 2007). The authors have previously examined the effects of slow orders on rail traffic flow and operating costs (Lovett et al. 2017), so this paper will focus on estimating the rate of slow order occurrence related to rail, crosstie, and ballast defects.

Slow orders are applied to a track segment when it is found to be unsuitable for operation at the posted maximum allowable speed (MAS). These conditions arise after the track structure has been disturbed for maintenance or when track defects are detected. Slow orders caused by track disturbance typically require speeds to be reduced to 10-20 mph (16-32 km/h) for approximately 0.2 million gross tons (MGT) of traffic while the track stabilizes (Selig & Waters 1994). This process is a routine part of maintenance activities such as tamping and crosstie renewal and can be incorporated into the cost of these activities during the maintenance planning process. Therefore, slow orders for track disturbed by routine maintenance activities are not explored in detail in this paper.

Defect-caused slow orders are unexpected events that are difficult to predict and explicitly consider in maintenance planning. Various analytical and probabilistic models can estimate the frequency of track defects that require the railroad to impose a slow order. In this paper, this rate of defects resulting in slow orders is termed the “slow order rate.” The estimated average slow order rate on a specific track segment can be used to determine the expected cost of slow orders and unplanned maintenance due to track defects in a given year. Understanding how the slow order rates change over time, and the factors that influence them, will also give insight into how capital maintenance timing affects the total cost of track ownership and operation. This paper will examine how to predict the slow order rate for three major track



components: rail, crossties (sleepers), and ballast, and apply it to capital track maintenance planning. For this paper, ballast defects include alignment and surface defects, and maintenance activities to repair these defects are classified as ballast maintenance.

Although railroads can have their own maintenance standards that establish criteria for when to impose slow orders, they are also subject to government-defined standards designed to ensure a minimum level of safe train operations. Since the United States Federal Railroad Administration (FRA) Track Safety Standards (TSS) are typically the same as the Canadian regulations and apply to more miles of track, they will be taken as representative of typical North American operations (Transport Canada 2011; Federal Railroad Administration 2014). Generally, the track geometry tolerances in the TSS vary according to track classes with each track class having a prescribed MAS. Internal rail defects are the exception because the type and size of the defect, rather than the operating speed, determines the remedial action. As the track class, and associated MAS, increases the allowable tolerances decrease. When the measured in-service track geometry exceeds tolerances, prescribed remedial actions are required on that track segment until maintenance can correct the defect (Federal Railroad Administration 2014).

2 SLOW ORDER COSTS

Although this paper will focus on the slow order occurrence rate, it is helpful to understand the costs associated with slow orders since both rate and consequence are required to estimate risk. As with most disruptions to rail traffic, slow orders result in both direct and indirect costs that vary with the nature of the defect as well as maintenance and operational factors.

2.1 *Direct maintenance costs*

Direct costs are those associated with performing localized maintenance to repair the defect and remove the slow order, including labor, materials, and equipment. This localized, or “spot,” maintenance is typically not intended to return the track to a perfect state. Spot maintenance is also relatively inefficient due to its small scale, short work windows, and reactive nature (Shimatake 1969; Esveld 2001; Zoeteman 2004; Burns & Franke 2005; Grimes & Barkan 2006; Lovett et al. 2015c).

Direct slow order costs follow a traditional risk formulation since the expected costs are the defect rate times the cost per defect. These costs are largely dependent on the track component associated with the defect since different types of remedial action are required for each defective track component. For internal rail defects, a new section of rail,

approximately 20 feet (6 m) long, is welded in to replace the section containing the defect (American Railway Engineering and Maintenance-of-Way Association 2012). Ballast-related defects are typically corrected by localized tamping. Other components, such as crossties, require local replacement of a sufficient number of the defective units to meet the required specifications (Riley & Strong 2003; Federal Railroad Administration 2014). Railroads usually track the cost of these activities and can apply them in maintenance planning.

2.2 *Indirect costs*

Train delay is the primary indirect cost for slow orders. Lovett et al. (2017) developed a closed-form model for estimating train delay associated with a given number of slow orders and operating conditions. Since this formulation includes the slow order rate, the risk is effectively the output. It also considers the interaction between slow orders, the effects of which will be discussed further in Section 4. After the amount of train delay is computed, it must be multiplied by a train delay cost that considers the operational characteristics of traffic operating on the line (Lovett et al. 2015a).

3 PREDICTION MODELS

To predict the approximate number of slow orders on a track segment in a given year, probabilistic models were used to determine the average annual defect rate per mile. While interactions between track components may increase the local occurrence of defects once one component fails, no models were found that consider these interactions. Therefore, this paper treats each of the major track components independently.

3.1 *Rail slow order prediction*

There are a variety of rail defect types identified by the FRA, each with one or more possible remedial actions based on defect severity (Federal Railroad Administration 2014). This analysis will focus on transverse fissures as most rail defects are given this categorization until they are removed from service for further examination (Sperry Rail Service 1999). Orringer (1990) developed a model to calculate the expected number of defects per mile based on the accumulated tonnage on the rail, inspection interval, and historical ratio of service to detected defects that was modified by Lovett et al. (2017). Detected defects are found through inspection, while service defects are those that result in a broken rail. The Orringer model focuses on detail fractures, a subset of transverse fissures because they were the type of rail defect causing the most rail breaks when the analysis was performed (Liu et al. 2014), but the concept can be applied to all rail defects. Only

detected defects will be addressed here because service defects may require more extensive remedial actions including stopping service on the line (Federal Railroad Administration 2014). Orringer's original formulation was modified to use the cumulative distribution function, rather than a probability density function, which makes the model more accurate and computationally simpler. The detected rail defect slow order rate is calculated by:

$$R_{SO,R}(y_R) = N_{Rail} \frac{e^{-\left(\frac{y_R N_A}{\beta_R}\right)^{\alpha_R}} - e^{-\left(\frac{(y_R+1)N_A}{\beta_R}\right)^{\alpha_R}}}{1 + \lambda(\Delta N - \theta)} \quad (1)$$

where $R_{SO,R}$ = annual detected rail defect rate per mile; N_{Rail} = number of rail sections per mile (273 (Orringer 1990)); y_R = years since rail replacement was performed; N_A = annual tonnage (MGT); ΔN = average tonnage between rail inspections (MGT); θ = minimum inspection interval (10 MGT (Orringer 1990)); λ = proportionality factor (0.014 (Orringer 1990)); α_R = Weibull shape factor (3.1 (Davis et al. 1987; Liu et al. 2014)); and β_R = Weibull scale factor (2150 (Davis et al. 1987; Liu et al. 2014)). While the model is dated, it is still used by the FRA to determine rail flaw inspection intervals (Volpe Center 2014), and the parameter values are the most recent that could be found in the literature. New research is ongoing to develop new rail defect prediction models that can be used for this purpose (Davis et al. 2016).

3.2 Crosstie slow order prediction

The FRA TSS require a minimum number of crossties in good condition within each 39-foot section of track based on the MAS and track curvature (Federal Railroad Administration 2014). The Forest Service Products Curve (FSPC) can be used to determine the failure probability of timber crossties as a function of the ratio of the crosstie age to the average crosstie life (MacLean 1957), but this only gives the probability of failure for crossties of a single age. The nature of crosstie renewals is that only one-quarter to one-third of the crossties are replaced during each cycle, leading to multiple crosstie cohorts of varying ages. Lovett et al. (2015b) developed a process to determine the probability of an FRA TSS defect occurring over a 39-foot section of track given a certain amount of time has elapsed since a crosstie renewal using:

$$R_{SO,T}(y_T) = (P_{39}(y_T + 1) - P_{39}(y_T)) \times \frac{5280}{39} \quad (2)$$

$$P_{39}(y) = \sum_F \prod_{j=1}^k \binom{n_j}{i_j} p_j^{i_j}(y) (1 - p_j(y))^{n_j - i_j} \quad (3)$$

$$p_j(y) = 1 - \exp\left[-\left(\frac{y+(j-1)c}{\beta_T A}\right)^{\alpha_T}\right] \quad (4)$$

where: $R_{SO,T}$ = annual number of crosstie related slow orders per mile; y_T = number of years since crosstie renewal; F = set of failed crosstie combinations not resulting in an FRA TSS defect in a given 39 foot (12 m) section of track; k = number of crosstie age groups; n_j = number of crossties in age group j ; i_j = number of failed crossties in age group j ; c = time between capital crosstie replacement; A = average crosstie life; α_T = crosstie Weibull shape factor (4.56); β_T = crosstie Weibull scale factor (1.02); and other variables as previously defined. Equation (4) represents the Weibull distribution approximation of the FSPC used as the occurrence probability for the Binomial distribution in (3).

Since the original FSPC found failure rates based on the age of a crosstie relative to the average crosstie life, the shape and scale factors in (4) do not need to consider the operating conditions directly because they can be factored into the average crosstie life. This model assumes regular crosstie replacement cycles where a set number of crossties are replaced per mile in each crosstie renewal. If the replacement cycle or number of crossties replaced is not constant, (4) will need to be modified to consider the initial age of each crosstie cohort at the beginning of the analysis period.

3.3 Ballast slow order prediction

Similar to rail defects, there are a variety of defect types associated with the track geometry surface and alignment, but all track geometry defects attributable to ballast defects require the same general types of remedial actions and corrective maintenance (Federal Railroad Administration 2014). Previous research in this area has focused on the standard deviation of various alignment measurements (Shimatake 1969; Oh et al. 2006; Chang et al. 2010). Since North American track geometry tolerances are based on absolute deviations (Federal Railroad Administration 2014), a new model was developed based on the methodology of Alemazkoor et al. (2015). The data set used was originally released for determining defect progression and did not explicitly include maintenance data (INFORMS Railway Applications Section 2015). To infer the timing of maintenance from the supplied data, if an FRA TSS defect was detected and no defects were detected within 100 feet on either side on a subsequent inspection, it was assumed that capital maintenance was performed. The data were then fit to a Weibull distribution.

Since there is no defined average life of a ballast defect, as is the case in the FSPC, the scale factor will need to vary based on the operating conditions. This can be done by having the scale factor be a function of the specific explanatory variables that are most significant for a particular route or section of track (Mishalani & Madanat 2002; Kleinbaum &

Klein 2012; Alemazkoor et al. 2015). For the data used, only considering the time since capital maintenance resulted in the most accurate model, but this will not always be the case, so a more general form is presented here. Unlike rail and crossties, typical ballast maintenance to eliminate track geometry defects does not involve replacing the ballast section outright with new material. Since the ballast is not truly “new,” it is assumed that ballast defects will return each subsequent year that capital maintenance (undercutting) is not performed. This means that all expected ballast defects since capital maintenance was performed need to be considered in a cumulative manner, rather than just those occurring for the first time in a given year as in the rail and crosstie models. The ballast-related slow order rate is calculated by:

$$R_{SO,B}(y_B) = (P_{200}(y_B + 1)) \times \frac{5280}{200} \quad (5)$$

$$P_{200}(y) = 1 - \exp\left[-\left(\frac{y+365}{\beta_B}\right)^{\alpha_B}\right] \quad (6)$$

$$\beta_B = \exp(\Phi X) \quad (7)$$

where $R_{SO,B}$ = annual number of ballast-related slow orders per mile; $P_{200}(y)$ = probability of a given 200-foot section of track developing one or more surface or alignment related defects at time y ; y_B = years since undercutting was performed; α_B = ballast shape factor (1.088); β_B = ballast scale factor (8,862); Φ = row vector of coefficients; and X = column vector of explanatory variables.

4 CASE STUDY

The models discussed in Section 3 were applied to a hypothetical 100-mile (160 km) section of 40 mph (64 km/h) track (FRA Class 3) handling 30 MGT annually. Based on industry averages, this tonnage level equates to approximately 12 one-mile long trains per day (Association of American Railroads 2015). Rail defect slow orders result in a speed reduction to 30 mph (48km/h), while crosstie and ballast-related slow orders result in 25 mph (40 km/h) maximum speeds (Federal Railroad Administration 2014). This case study assumes all trains operate at the MAS but average operating speeds could also be used. Rail defect inspections occur every 15 MGT and rail defects cost \$895 to repair (Liu et al. 2014). Crossties have a 20-inch (51 cm) spacing on-center, 30-year average life, and a nine-year renewal cycle (Lovett et al. 2015b). Crosstie defects are corrected by replacing three crossties for a total cost of \$285 (Zeta-Tech Associates Inc. 2006). Ballast slow orders cost \$1,200 to repair based on an industry source for the cost of spot tamping. Inspections for crossties and

ballast occur once per week (Federal Railroad Administration 2014). All slow orders are applied on the 0.1 mile (0.16 km) section of track surrounding the defect. The duration of rail, crosstie, and ballast slow orders are assumed to be one, four, and three days, respectively. It is assumed that normal operations use 65% of the line capacity of the route (Cambridge Systematics 2007; Lovett et al. 2017), accelerating and decelerating out of and into slow orders adds an additional 15 minutes to the run time (Lovett et al. 2017), and train delay costs \$950 per train-hour (Lovett et al. 2015a).

4.1 Direct, delay, and total cost comparisons

The defect rates for each component under the above case study parameters were calculated over a range of conditions expected during the duration of a typical maintenance cycle for that component (Fig. 1). The “defect repair” curves correspond to the equations in Section 3. These curves can be compared to the “no repair” curves that show what the theoretical defect rate would be if the defects were not repaired. The ballast curve is the exception since it is assumed that the defect rate will include both the new defects that develop during the year and all of the previously maintained ballast defects as well reoccur during the year. If the ballast defects were not maintained, the number of defects would increase at approximately the same rate but the severity would increase. Realistically, the components degrade until an acute failure, such as a rail break, occurs so the “no repair” situations will not be examined further.

Comparing the defect repair curves for each component reveals that they each perform differently. Rail defects exhibit a gradual growth that stays relatively low compared to the other components. Crossties perform quite differently since there are almost no defects during the first 12 years after a crosstie renewal, but then a drastic increase after that. This is because Class 3 track only

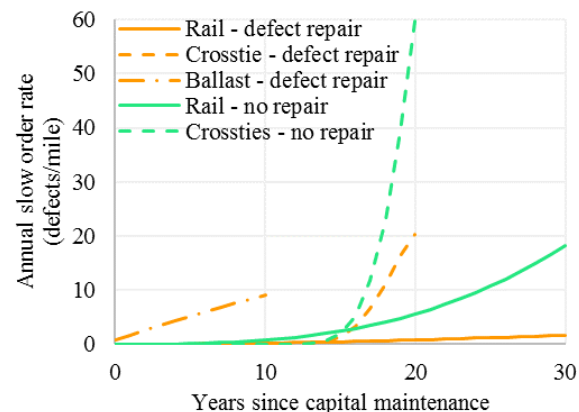


Figure 1: Slow order defect rate for the major track components with and without spot maintenance

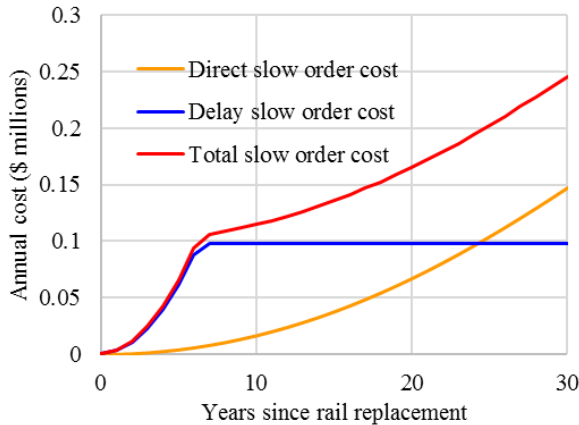


Figure 2. Annual cost of rail-related slow orders vs. years since capital maintenance

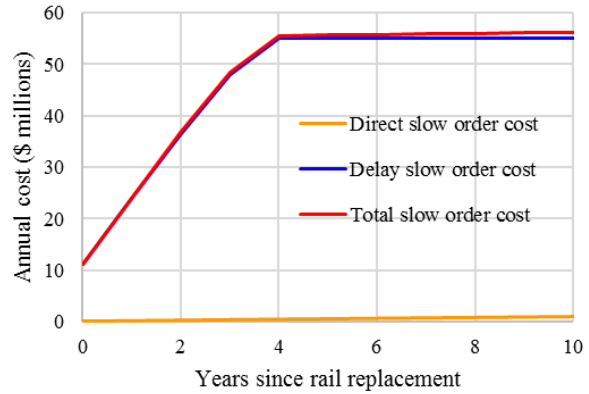


Figure 4 Annual cost of ballast-related slow orders vs. years since capital maintenance

requires eight cross-ties in good condition per 39 feet (12 m) to be free of defects (Federal Railroad Administration 2014). For a defect to develop, almost all of the cross-ties installed before the most recent renewal would need to fail. Once the cross-ties from the two most recent renewals have a larger probability of failure, the compounded failure probability increases rapidly. This also explains why Lovett et al. (2015b) found that cross-tie slow order risk would not materially influence maintenance decisions because they only calculated slow order costs until the ninth year after a cross-tie renewal.

Further insight is gained by comparing the total, direct, and delay slow order costs for each component (Figs. 2-4). Each plot shows the region where the defect rate increases until there are enough defects that the entire route is effectively subject to speed restrictions, as evidenced by the plateau in the delay cost curve. The shape of the delay cost curve, including the plateau location, changes based on the traffic, train performance, and slow order characteristics (Lovett et al. 2017).

For rail (Fig. 2), the train delay costs are on the same order of magnitude compared to the direct

costs since the slow order duration is short and the inspections only occur twice per year. The other extreme is observed for cross-ties (Fig. 3) and ballast (Fig. 4) where accumulated delay renders the direct costs of repair almost negligible. An increase in delay costs would be expected since the cross-tie and ballast slow orders are left in place longer, but the increase is much greater than expected based on the relative increase in the slow order duration (Lovett et al 2017). The key difference is the number of inspections taking place during the year. The rail slow orders are concentrated after only two inspections and are only in place for 24 hours, so there is a long period of time when no slow orders are being placed. For cross-ties and ballast, a new set of slow orders are being placed every week, so even though the delay associated with a single slow order differs by only one order of magnitude, the delays are incurred much more often.

4.2 Comparison of alternative maintenance timings

Although it is interesting to look at how the slow order costs change over time, a primary benefit of these curves is to aid in capital maintenance planning. In Figures 2-4, the area under the total cost curve represents the slow order cost for each component in a given planning period. Performing capital maintenance during the planning period will decrease the slow order cost associated with the new component during subsequent years but the savings need to be balanced against the expense of performing the capital maintenance. This can be done by comparing the slow order costs for different capital maintenance timings within the planning period (Figs. 5-7).

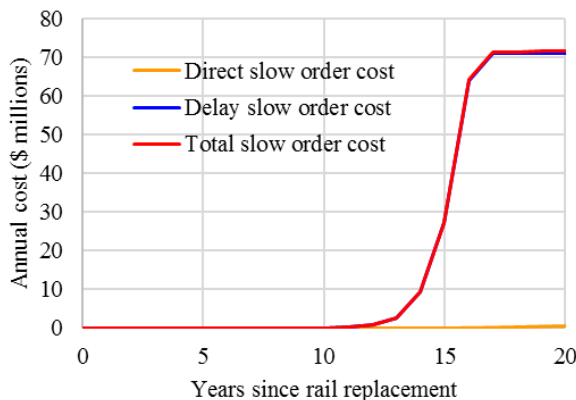


Figure 3. Annual cost of cross-tie-related slow orders vs. years since capital maintenance

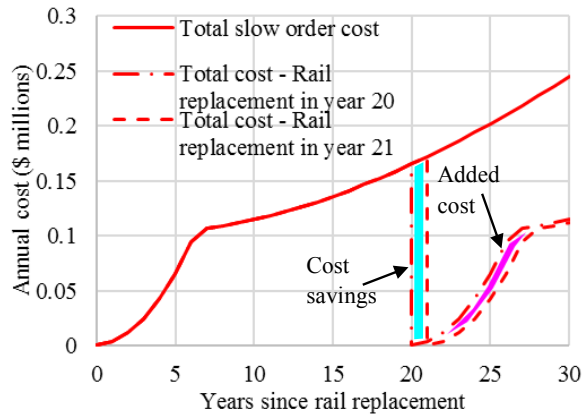


Figure 5: Rail slow order cost under different rail replacement schedules

For rail (Fig. 5) and crossties (Fig. 6), performing maintenance earlier initially reduces the slow order cost by a noticeable amount, but comparing the slow order costs for rail in later years shows that the annual slow order cost is higher for the earlier replacement curve. That is to be expected since it has been longer since capital maintenance was performed. Over time, the higher slow order cost combined with costs to perform capital maintenance earlier may counteract the initial slow order savings, showing that a longer-term perspective is required for maintenance planning.

Comparison of ballast maintenance schedules (Fig. 7) shows a different perspective because capital surfacing is performed multiple times within the illustrated 10-year planning period. Since the 3-year capital surfacing interval would require more maintenance instances than the 4-year interval, the capital costs will be higher, further offsetting the slow order cost reduction. This shows that the selection of the planning window is also an important factor when comparing proposed maintenance schedules since it will influence the number of times maintenance will need to be performed.

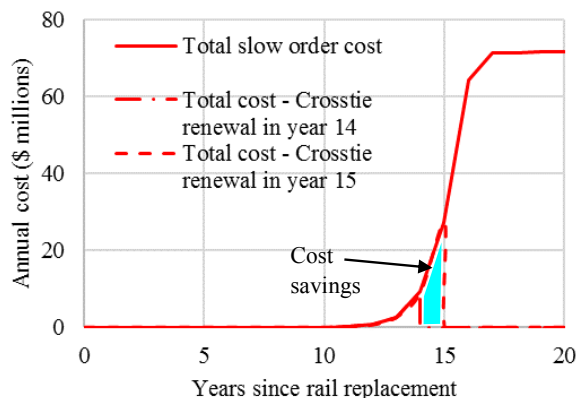


Figure 6: Crosstie slow order cost under different crosstie renewal schedules

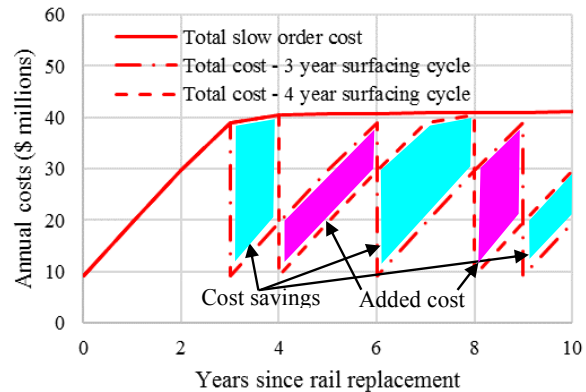


Figure 7: Ballast related slow order cost under different capital surfacing schedules

5 CONCLUSIONS AND FUTURE WORK

This paper has presented an approach to predicting the cost of slow orders and how to use them for maintenance planning. One of the key findings of this research is the impact of train delay on the cost of slow orders. In almost all cases, the train delay costs are larger than the direct cost to repair the track defect causing the slow order. The exception being in the rail case where the two costs are within an order of magnitude of each other. For the crosstie and ballast slow orders, the delay costs are high enough that the delay costs are orders of magnitude lower than the delay costs even after the delay costs have plateaued. The driving factor behind these different behaviors is the number of inspections during the year. Fewer inspections coupled with short slow order duration results in the delay costs being very low, but as either the number of inspections or the slow order duration increases, the delay costs can rise very rapidly. The substantial contribution of train delay to total costs shows how important it is to consider the operational impacts of slow orders and track defects when planning maintenance intervals.

The effects of train delay and the nature of the operational impact of slow orders provide key inputs to a maintenance plan. While performing capital maintenance earlier will decrease the immediate slow order costs, additional costs are incurred in later years after the track components have degraded. Quantification of the slow order impacts allows the capital maintenance plan to be optimized by balancing the slow order and capital maintenance costs. Additionally, if spot maintenance is made more efficient, effective, and timely it can reduce the overall costs and recurrence of slow orders while increasing the time between capital maintenance activities.

One area where this work can be made more robust is by gathering new data from the railroads and either validating these findings or developing



new models that reflect the current quality of materials and maintenance practices. A new analysis could also take advantage of “big data” techniques such as machine learning that were not available for development of the rail and crosstie models referenced by this paper. Analyzing new data would also allow for comprehensive slow order models that consider the condition and maintenance history of the entire track structure rather than a single component. Applying the findings and methodology from this research to new probabilistic models will allow railroads to more effectively optimize their maintenance strategy by using a more holistic planning approach.

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