

Cost and Delay of Railroad Timber and Concrete Crosstie Maintenance and Replacement

Alexander H. Lovett, C. Tyler Dick, Conrad Ruppert, Jr.,
and Christopher P.L. Barkan

Because railroad crossties are the second most valuable railroad asset, it is critical that they be maintained and managed in a cost-effective manner. The direct expenses of track maintenance cost railroads billions of dollars each year, and additional millions are spent on recovery from track-caused derailments. Train delay costs further increase the consequences of unplanned track outages. Additionally, maintenance activities often result in traffic disruptions and congestion that can propagate throughout the rail network; this effect is a concern especially on higher-density lines that are vulnerable to cascading train delay and longer postincident recovery times. Compared with timber crossties, concrete crossties offer several potential benefits but also have a greater initial cost. Economic analysis can show instances in which extra capital investment in premium components is justified. Such analysis can also aid in planning general tie maintenance by balancing the costs of added maintenance with the associated benefit of reduced accident risk. This paper presents a model for evaluating the life-cycle economics of tie types by comparing concrete and timber crossties. A sensitivity analysis demonstrates how various inputs affect the cost comparison between timber and concrete ties.

North American railroads spend billions of dollars each year on track maintenance, and crossties are one of the largest expenditures (1). Hence crosstie investments should be made on the basis of sound economics and maintenance performed in the most cost-effective manner. Track maintenance strategies differ in how frequently various components are renewed. In all cases, there is a wide range of associated costs that vary depending on operating conditions and that affect which alternative is the most cost-effective.

For an accurate assessment of the cost-effectiveness of a maintenance procedure, the initial direct cost of labor and materials cannot be considered in isolation. Previous research discussed life-cycle costing (LCC) for track maintenance and construction (2–6). However, initial and recurring direct costs of labor and materials are not the only costs that should be considered. In a practical working railroad environment, it is difficult to perform all required maintenance without delaying train operations. Transportation and engineering departments frequently compete for track time. Delay costs related

to track maintenance may be incurred by trains using the line undergoing maintenance but may also affect other parts of the network. Traffic density on North American railroads is expected to increase, exacerbating the delay associated with maintenance (7). If the overall impacts and costs of maintenance-caused train delay are not fully accounted for, suboptimal decisions regarding infrastructure investment and maintenance strategies may result. Specific to the comparison of concrete and timber ties, a frequently cited economic analysis of North American crossties states that its analysis methods do not adequately account for the maintenance differences between the two tie types (8, 9). Hence a new method is needed for an understanding of the economic comparison between these two types of crossties.

LIFE-CYCLE COSTS

Life-cycle cost analysis is best applied in situations in which the asset has substantial upkeep costs. The analysis must consider not just the costs directly related to the component in question but also any costs affected by the component selection (10). The methodology set forth in this research considers four main cost categories: renewal, accident, slow order, and other track maintenance. Each of these categories can be further divided into direct, delay, and network costs. Previous research on track maintenance considered direct costs, and some studies included delay costs in their LCC analyses, but none appear to have factored in network effects or additional delay during the time needed for normal service levels to resume after the track has reopened (2, 6, 11). An understanding of network effects and delay beyond just those trains interrupted by the track outage is necessary because these effects can have significant consequences for the indirect costs of track maintenance.

Two parameters essential to LCC analysis are the discount rate and the analysis period. The applicable discount rate for an LCC analysis will vary between owning entities and is based largely on the cost of capital. Correct selection of the discount rate can have a substantial impact on the results of LCC and other present-value cost analysis techniques. Higher discount rates will favor alternatives with comparatively low initial costs and higher operating costs, such as timber tie track, and lower discount rates will favor the opposite conditions, such as track constructed with concrete crossties (12, 13).

The period considered by an LCC analysis is based on the lifetime of the components in question (10, 14). For crossties, this is somewhat ambiguous as timber crosstie track does not necessarily have a finite lifetime. Failed ties are renewed as needed at a rate

Rail Transportation and Engineering Center, Department of Civil and Environmental Engineering, University of Illinois at Urbana–Champaign, 205 North Mathews Avenue, Urbana, IL 61801. Corresponding author: A. H. Lovett, alovet2@illinois.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2476, Transportation Research Board, Washington, D.C., 2015, pp. 37–44.
DOI: 10.3141/2476-06

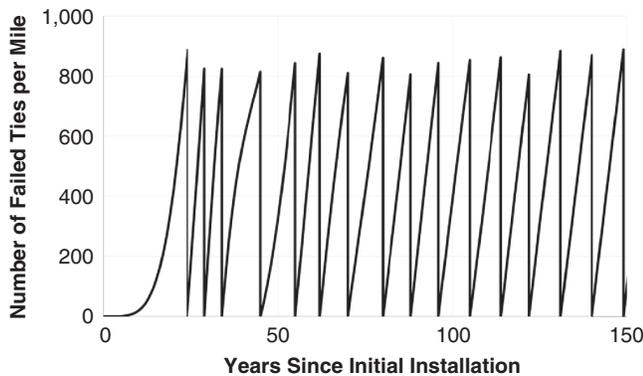


FIGURE 1 Failed timber tie replacement pattern for 20-in. tie spacing and 30-year tie life.

that will vary depending on operating conditions, such as climate and traffic levels, and tie renewal threshold (15). A commonly used approach for determining the distribution of ages of failed timber crosstie is the U.S. Forest Service products curve (FSPC) (15–17). Previous research showed that tie replacements are most efficient when more than 800 ties are replaced at a time (18). Hence, the authors developed a model that uses FSPC to predict years when a track is expected to have more than 800 failed ties per mile; the prediction is used to determine when and how many degraded ties need to be replaced. This model was used to determine when renewals will take place for a track with 20-in. (508-mm) tie spacing and average tie life of approximately 30 years. The number of failed ties in each year is shown in Figure 1. Tie replacements occur every 9 to 10 years when between 800 and 900 ties per mile have failed. For the analysis, the renewal rate was set at 850 timber ties per mile every 9 years. In practice, railroads can use historical maintenance data to develop average tie renewal rates for specific track segments as the average tie life will vary depending on operating conditions and environmental factors.

Concrete ties typically are modeled as being renewed out-of-face, that is, every tie is replaced, at the end of their estimated 40- to 50-year service life (19–21). This approach is more like a typical component replacement and makes for a simpler LCC analysis. Concrete tie life was taken as 45 years, as this was an average value and resulted in the concrete tie life being a multiple of the timber tie renewal cycle, with the LCC time horizon finishing the year before a renewal for both alternatives. Concrete ties have not been in service in North American heavy haul applications long enough to achieve a satisfactory estimate of the exact circumstances when end-of-life cycle replacements will take place and what the costs of replacement will be.

Direct Costs

Renewal Costs

Direct renewal costs (i.e., labor and materials) can be determined in several ways. One method uses unit equipment, labor, and tie costs and would be reasonable for a railroad or other entity with access to current values (18). However, this method's results would be questionable if historical costs were simply updated to current dollars without an understanding of how relationships between the parameters have changed with the development of new maintenance techniques and equipment. Another method uses published industry

values of tie installation costs. The Railway Tie Association (RTA) uses \$95 per timber tie and \$200 per concrete tie installed, including all material and labor costs (9). Although these values were used for analysis in this paper, some industry sources cite a lower concrete tie cost. The impact of varying tie cost is examined in the sensitivity analysis. In the LCC, these values are multiplied by the number of ties replaced during each renewal for determining the direct cost.

Accident Costs

Accidents are an unscheduled event that can be modeled by average frequency and consequence. FRA maintains a database of rail accidents with damages above a monetary threshold (22); however, this database includes little information about the track structure at derailment locations. Thus to make comparisons between the accident rates and costs on concrete tie and timber tie track, additional analysis that used track structure data provided by a Class I railroad was conducted.

The railroad data indicated that 17% of track-caused accidents occurred on concrete tie track. However, this rate must be normalized by ton-miles as not all track has the same annual tonnage, and industry professionals indicate that concrete ties typically are used on track segments having more traffic. The length of concrete tie track on the railroad was estimated by assuming that 6.5% of all ties are concrete (23) and assuming a standard concrete tie spacing of 24 in. (609.6 mm). The railroad also provided the average annual tonnage for concrete and timber tie track. Using this tonnage resulted in a concrete tie track accident rate of 0.152 per billion ton-miles (0.104 per billion megagram-kilometers) and a timber tie track accident rate of 0.208 per billion ton-miles (0.142 per billion megagram-kilometers). A causal relationship with tie type is not to be inferred here. Accident rates vary depending on several factors, including track class and annual tonnage (24), that were not accounted for in this preliminary analysis. Concrete ties generally are used in track with higher tonnage and FRA track class. Both factors are correlated with a lower accident rate. In contrast, timber ties are widely used in track with a variety of FRA track classes and annual tonnage. These relationships make it difficult to determine how much of the accident rate variability comes from the tie type. Additional railroad data will enable development of accident rates for track with each type of tie and track class combination that are better aligned with specific operating conditions than the preliminary values presented here. In the absence of these detailed rates, the preliminary values are used here to illustrate the analysis process.

The cost of an accident is also likely to differ between the two tie types. Based on the FRA database for 2011 to 2013 and the location of concrete ties, the average cost of a track-caused accident was \$363,811 for accidents on concrete tie track and \$218,850 for timber tie track (25). Accident costs on concrete tie track may have higher costs because they typically need to be replaced after each derailment, but timber ties are more resilient. Indirect costs such as delay or network effects are not accounted for in the FRA data, so these costs must be taken into consideration in specific scenarios.

Slow Order Costs

Like accidents, slow order costs are modeled according to their frequency and cost. For each track class, the FRA track safety standards specify the required number of good ties for tangent and curved

track (26). Tracks that do not meet these criteria are subject to slow orders, by which train operating speed is reduced until maintenance is performed. The expected number of slow orders caused by cross-tie degradation can be calculated in a method similar to the Poisson process by using a Weibull approximation of FSPC and average tie replacement rate. The formulation developed for this method is given in Equations 1 and 2. The Weibull distribution was selected because it had been used in other tie life studies and fits the data better than other models (27).

$$P_{39} = \begin{cases} 1 - \sum_{i_j=0}^f \prod_{j=1}^k \binom{n_j}{i_j} p_j^{i_j} (1-p_j)^{n_j-i_j} & n_j \geq i_j \quad \forall j \\ 0 & \text{else} \end{cases} \quad (1)$$

$$p_j = 1 - \exp \left[- \left(\frac{y + (j-1)c}{\beta A} \right)^\alpha \right] \quad y + (j-1)c > 0 \quad (2)$$

where

- P_{39} = probability of slow order in average 39-ft track segment,
- f = maximum allowable number of failed ties,
- k = number of age groups,
- n_j = number of ties in age group j ,
- i_j = number of failed ties in age group j ,
- p_j = failure probability of tie in age group j ,
- y = years since last tie renewal,
- c = years between tie renewals,
- A = average tie life, and
- α, β = Weibull shape parameters corresponding to FSPC.

The calculated probability represents the average number of slow orders per 39 ft of track during a given year and can be multiplied by the number of track miles to find the expected number of slow orders per year. This rate is calculated on an annual basis because the probability will change as the ties age and will reset after each tie renewal. It is assumed that once a slow order is repaired, the presence of newer ties will reduce the expected number of slow orders in subsequent years. Individual railroads have their own operating protocols that may impose slow orders under other tie failure conditions (e.g., tie clusters) and will affect this probability calculation (28, 29). This methodology can be adapted to specific operating protocols, but because the FRA standards are applicable to all railroads, they were used for this analysis.

The direct costs for each slow order consist of the labor and material costs of replacing sufficient ties to meet the FRA standards. For this analysis, it was assumed that two ties are replaced for each slow order. The cost of replacing the two ties is multiplied by the expected number of slow orders per year to calculate the annual direct slow order cost.

Other Track Maintenance Costs

Other track maintenance related to tie condition was assumed to consist of rail maintenance and tamping. Previous research showed that timber tie quality has an insignificant impact on rail maintenance (18), but concrete tie manufacturers claim that concrete ties improve rail life (30, 31). However, because no independent data were available that support this claim, it was not considered in this analysis. Improved tie quality has been shown to result in decreased surfacing

costs (18), although this finding was based on timber ties. It was assumed for this study that concrete ties equate to good tie conditions and therefore have lower surfacing costs. Discussions with railroad personnel and concrete tie manufacturers suggested that concrete ties hold line and surface better, so it was also assumed that concrete tie track would need to be surfaced less frequently than timber tie track (30, 31). Specific maintenance costs and frequencies are given in subsequent sections.

Delay and Network Effects

Since the impact of train delay is not necessarily limited to the line on which a service disruption takes place, this paper considers the costs of both primary and secondary delays. Primary delay is the delay directly associated with trains on the disrupted track; secondary delay accounts for network effects that lead to delay costs associated with other trains on the network.

Primary delay is calculated as the increased travel time associated with a service disruption. The extra travel time may be a result of trains being rerouted onto a longer line or delayed because the system has less flexibility with a portion of the track out of service. The increased travel time is applied to all trains that would be affected by the disruption. For track maintenance, this time is likely a few hours a day over several weeks. However, for unplanned disruptions track repair could take 24 h or more, because unplanned disruptions do not allow for prior scheduling of reroutes.

For determining the increased travel time, several options are available, including rail traffic simulation and parametric delay-volume curves. Simulation allows specific track and traffic configurations to be tested, but new track layouts must be developed for every track configuration. A railroad that is already using simulation software could reasonably use this method by drawing from its library of network simulation models. However, for general use in a wide range of situations without specialized software, a more analytical approach would be beneficial. Parametric models, such as the delay-volume curves developed by Sogin et al. (32) and Shih et al. (33) and generalized into Equation 3, are well suited to this analysis.

$$D = (S_1 - S_2 x) e^{kV} \quad (3)$$

where

- D = average train delay (min),
- S_1 = single track delay (19.5206),
- S_2 = delay mitigation constant (19.149),
- x = double-track percentage,
- k = congestion factor (0.0471), and
- V = traffic volume (trains per day).

For maintenance performed on double-track lines, the percentage of double track will effectively decrease during the maintenance work window. For maintenance on single-track lines, traffic must be stopped during the work window. For all lines, traffic will stop during postaccident repair, assuming that all tracks are removed from service after an accident. Closing all lines is a worst-case scenario, but repairs likely would be delayed because of safety concerns if adjacent lines were kept active. When the track is reopened following maintenance, a double-track section will eventually return to normal, but for single-track sections or after accidents there will be some residual delay. For single-track sections, the traffic is assumed to clear

before the next maintenance window. After accident cleanup, it will take approximately 2 days for the traffic to return to normal after the disruption is cleared, assuming traffic normally operates at 65% of theoretical capacity, which is slightly more conservative than the American Railway Engineering and Maintenance-of-Way Association recommendations (34). During this time the track will operate at its theoretical capacity to move as many trains as possible and minimize the length of the recovery time.

Network effects are more complex and can manifest in a variety of forms experienced by trains beyond those that typically run on the disrupted line. The most easily measured network effect is the delay experienced by traffic on other lines if trains have been rerouted around a disruption. Trains will be rerouted only if the alternate route results in less delay than if the trains continue on the original route. If a system is large enough, rerouting may result in delay being propagated through many lines as alternate routes reach capacity and traffic is further rerouted. This network effect can be measured in the same manner as direct delay. Use of a simulation tool will allow for the simultaneous calculation of both direct and network delay.

Additional delay can be experienced by railcars that miss their scheduled connections at intermediate yards. The cost of expected connection delay is a function of the distribution of train departure times from the yard and the value of the lading being shipped. Yards that are optimized to reduce the amount of time cars wait in the yard or to handle a large amount of high-value freight will have higher delay consequences because even small amounts of delay may result in a missed connection. Another form of network cost is a train crew exceeding the hours of service allowed under operating rules. When this occurs, a replacement crew must be transported to where the train has stopped and the old crew transported back. If the crew change was supposed to occur before the train moved to a new territory, the original replacement crew also will be delayed. For both conditions, specific circumstances are needed for evaluating these costs.

The cost of train delay per hour varies depending on a variety of factors that fall into five main categories: crew, cars, lading, locomotives, and fuel (35–37). Most of these costs vary with train and commodity composition. For an average train composition, crew, car, lading, and locomotive costs are approximately \$950 per train hour (37). Fuel costs are the most variable as they depend on the type of delay imposed on a train and the number and type of locomotives in the consist. If delay results in a train being stopped, such as in a complete track outage, then the train is assumed to idle for the additional time. In the case of running delay—for example, a train is rerouted to a longer route or is able to move on the line with additional delay because a siding or section of double track is being maintained—the locomotive is assumed to be operating according to the average locomotive duty cycle (38). Fuel cost is based on fuel consumption of a 4,300-hp main line locomotive at an average fuel price (39, 40), which results in an idle and a running delay cost of \$1,009 and \$1,505, respectively. These numbers can, and should, be adjusted to reflect the actual train composition and crew costs on a given line. If a train energy model is available in the train simulator being used, the fuel cost can be calculated while the delay is being determined.

Slow orders are a unique situation because trains continue moving over the track but must slow for a specific segment. The model conservatively calculates the amount of additional time a train will take to slow to reduced speed (assumed to be that of the next lower track class), traverse the slow-ordered track, then accelerate back to normal

track speed. The calculated time is applied to the expected number of slow orders over the line and priced at the running delay cost.

SENSITIVITY ANALYSIS

Some of the inputs required for this analysis may be difficult and expensive to gather for a large number of lines, so which inputs have the largest impact on the LCC must be understood. Knowledge of the influence of each factor allows analysts to concentrate on gathering input data that are most significant. Inputs with a lower impact can be approximated if they are not readily available (41).

Because situations with and without alternate routes involve substantially different considerations, the sensitivity analysis was performed for each case independently. A total of 39 input factors were considered, covering virtually all of the track, operations, and disruption characteristics. The inputs tested and the range of values used are given in Table 1. For the scenario with an alternate route, the alternate route characteristics were varied with the same base and bounds as the primary route. When an alternate route is present, a reroute ratio, or ratio of the length of the alternate route to the length of the main route, is also specified. Base route characteristics are based on the work of Sogin et al. to match the operating conditions for Equation 3 (32). Track possession, equipment setup times, tie renewal rates, tamping speeds and costs, and train weights are based on published values and industry averages and analyses (18, 40, 42–44). The upper bound was selected to be approximately double the base value, and the lower bound is about 10% of the base value. Some categories, such as track class and tie spacing, already have specific limits that were used to define the lower and upper bounds. Other exceptions are accident cost, which can be an order of magnitude higher for lines with hazardous material traffic; the minimum amount of double track, which is limited by the siding length and spacing; track possession time, which has to be long enough to allow work to be done; and the timber tie renewal threshold, which was limited by the tie LCC model developed by the authors. Use of a reasonable range of values allows for a more complete picture of how sensitive the outputs are to each of the inputs (45).

The arc elasticity method was used to compare the relative influence of each factor on the ratio of timber to concrete tie LCC. Elasticity measures how the output changes with respect to the inputs. If an input value is adjusted and the output changes in the same direction, then there is positive elasticity. Output changes that are opposite the input changes indicate negative elasticity. Arc elasticity uses percentage change to normalize results and remove the impact of use of different units (41, 46).

The results of the arc elasticity analysis are summarized in Figures 2 and 3, where the top 20 most influential factors for the no-alternate-route and alternate-route scenarios are plotted. The two scenarios share 15 of the top 20 factors. The remaining factors for the alternate scenario pertain to the alternate route, which implies that when an alternate route is available, its favorability can have a substantial impact on the selected tie type. Among the factors that are shared between the two scenarios is the delay cost, excluding fuel, which indicates that fuel costs, which are more difficult to determine than other delay cost components, do not have to be as precise. Many of the shared factors that affect direct costs (e.g., tie spacing or tamping frequency) also affect delay costs.

Some in the industry think the concrete cross-tie replacement cost value used by RTA is too high. This analysis shows that even a relatively small change in the concrete tie cost will have a large impact

TABLE 1 Sensitivity Analysis Categories and Values

Factor	Lower Bound	Base Value	Upper Bound
Track characteristics			
Degrees of curvature	1	2	4
Track class	1	3	5
Timber tie spacing (in.)	18	20	24
Concrete tie spacing (in.)	18	24	30
Route length (mi)	25	240	500
Siding or crossover spacing (mi)	1	10	20
Percentage double track	0.19	0.5	1
Reroute ratio	1	2	5
Operating characteristics			
Trains per day	3	30	60
Average train weight (tons ^c)	600	6,723	12,000
Delay costs less fuel (\$/train hour)	100	950	1,900
Running fuel cost (\$/train hour)	50	555	1,110
Idle fuel cost (\$/train hour)	5	59	100
Discount rate (%)	1	6	12
Disruption inputs			
Track possession time (h)	2	6.5	12
Equipment set-up and tear-down time (h)	0.25	0.5	1
Timber tie costs (\$/tie)	10	95	200
Timber renewal threshold (ties/mi)	600	800	1,000
Timber renewal speed (mph)	0.05	0.22	0.40
Timber average tie life (years)	3	30	60
Concrete tie costs (\$/tie)	20	200	400
Concrete renewal cycle length (years)	30	45	55
Concrete renewal speed (mph)	0.05	0.16	0.3
Timber accident rate (accidents per BTM)	0.01	0.208	0.4
Timber accident costs (\$/accident)	30,000	218,850	1,000,000
Concrete accident rate (accidents per BTM)	0.01	0.152	0.4
Concrete accident cost (\$/accident)	30,000	363,811	1,000,000
Slow order application length (mi)	0.01	0.1	2
Slow order application time (h)	0.5	5	10
Ties replaced to repair a slow order	1	2	5
Timber tamping speed (mph)	0.05	0.28	0.5
Timber tamping cost (\$/mi)	600	18,031	35,000
Timber tamping frequency (years)	0.5	2	8
Concrete tamping speed (mph)	0.05	0.28	0.5
Concrete tamping cost (\$/mi)	600	6,341	35,000
Concrete tamping frequency (years)	0.5	4	8

NOTE: BTM = billion ton-miles; 1 BTM = 1.46 billion Mg-km.

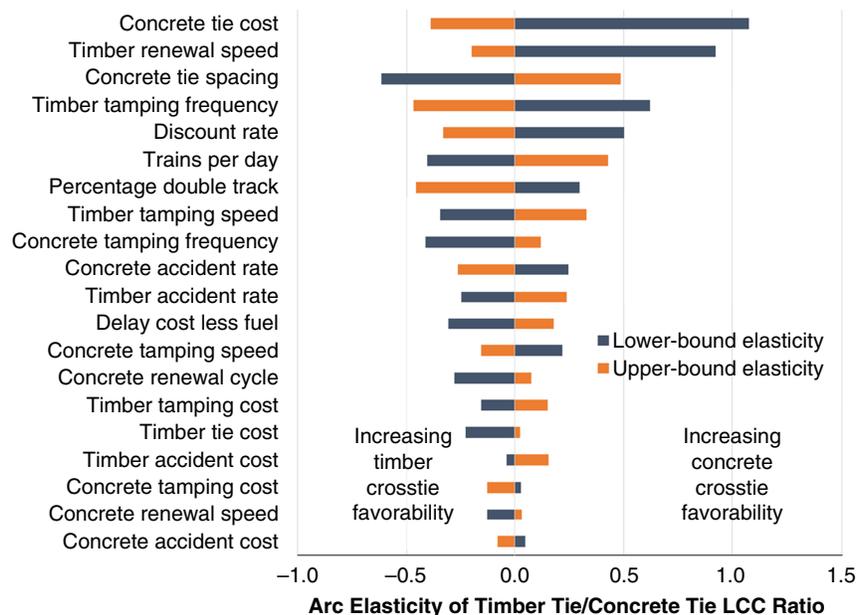


FIGURE 2 Sensitivity analysis results for route without alternate route.

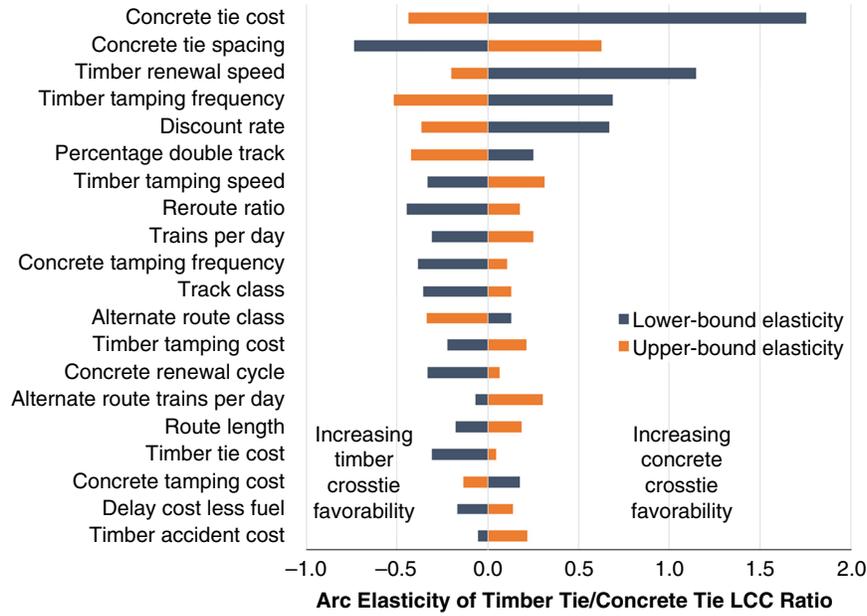


FIGURE 3 Sensitivity analysis results for route with alternate route.

on the favorability of concrete ties, likely because all concrete tie renewal costs are incurred in the first year and are not discounted, so these costs must be accurately estimated. The high sensitivity of the discount rate will increase its impact for organizations with a high discount rate, which will further bias the analysis toward timber ties. Hence organizations with different methods of computing the discount rate may come to different conclusions about preferred tie type even if all other factors are equal.

CASE STUDY

A case study was conducted with a network of four lines (Figure 4) and shows how the model handled various situations. All lines are FRA Class 4 track with moderate curves and climate, matching the conditions used to develop the timber tie renewal cycle and 30-year tie life assumption (17). The timber tie track is tamped every year.

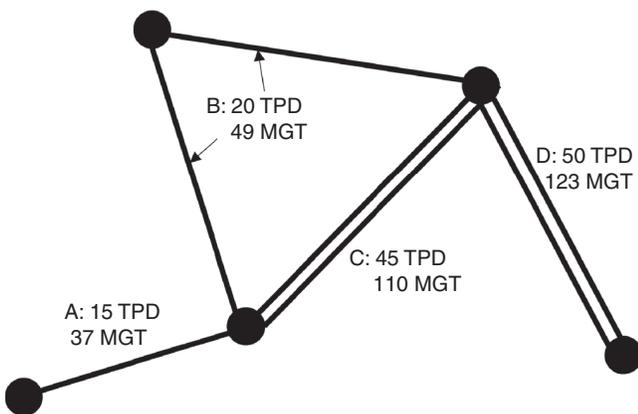


FIGURE 4 Case study network with segment traffic levels in trains per day (TPD) and million gross tons per year (MGT).

Single-track lines have 10-mi siding spacings and double-track lines have full double track. Except where other route-specific values are given, the remaining characteristics are the same as the base case in Table 1. It is assumed that there are no additional hours-of-service crew or yard delay costs.

Figure 5 shows the results of the case study broken down by category. On most of the routes, concrete ties are more cost-effective. For Line B, timber tie track may be more cost-effective because there is an alternate route that can be used during maintenance and accident recovery. When part of Line B is out of service, Line C may be an attractive rerouting alternative because of its double track and because it allows access to the customer at the midpoint of Line B. On Line C the delay does not have as big an impact because of the second main track. One cost that appears to have virtually no impact is the cost of slow orders, which was found to be orders of magnitude lower than the other cost categories. This is one of the most computationally intensive costs to calculate, so calculating specific data for this category may not be justifiable.

Accident costs are another category with unexpected results. Although the increased accident cost for concrete ties more than offsets their lower accident rate, the timber ties still have higher derailment costs. These higher costs are related to delay, which is the same for both tie types but is incurred more frequently in the timber tie scenario because of the higher accident rate.

Another perspective can be gained by separating the costs by type, as shown in Figure 6. Although delay costs typically do not make up the majority of the total cost, in all cases neglecting delay and network costs results in concrete ties being more expensive than timber. When delay is considered, concrete crossties become substantially more competitive and are even the low-cost alternative. On Line B, consideration of delay costs makes concrete ties slightly more competitive, and if recrew or yard delay costs are considered the balance may be changed. Line B is the only one to experience network delays because rerouting is not cost-effective for Line C. This fact can be a critical consideration in explanations to operations personnel about why maintenance or upgrades are needed.

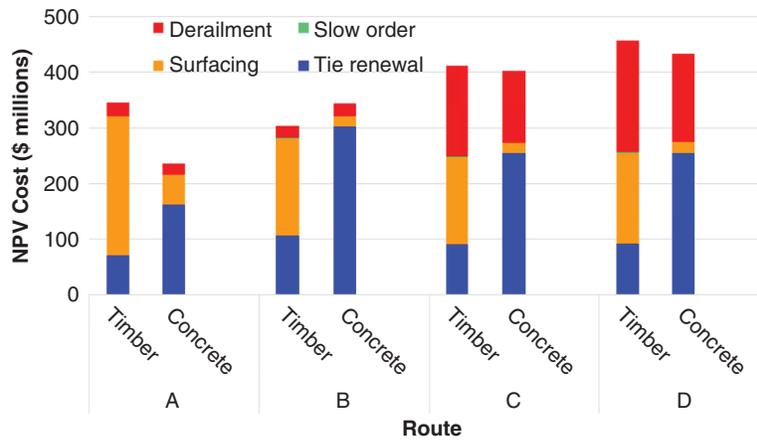


FIGURE 5 Case study results by cost category (NPV = net present value).

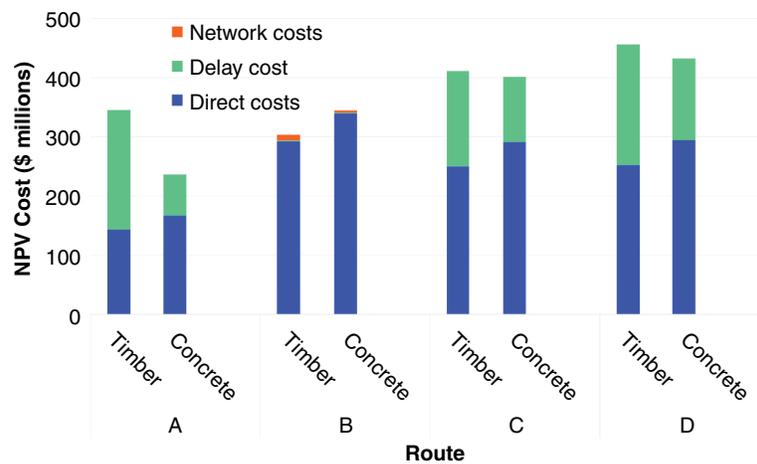


FIGURE 6 Case study results by cost type.

CONCLUSIONS

This analysis shows that consideration of delay and network costs can strongly affect maintenance decisions. Maintenance and infrastructure planners can use the results of the sensitivity analysis to identify where data collection efforts should be concentrated to ensure the accuracy of LCC analysis. The model’s sensitivity to concrete tie cost indicates that if the RTA values are too high, then any analysis using them may suggest timber ties are more favorable than they actually are. The sensitivity of the discount rate shows how organizations with different business objectives may draw different conclusions about what tie type is least expensive for a particular application.

The case study shows how delay and network effects can influence the comparison between timber and concrete ties and shows that even if direct accident risk is higher for a particular alternative, the option with the higher accident rate may have higher overall costs because of the increased frequency of network disruptions.

FUTURE WORK

The next steps for refining this model are to improve its applicability and validity. The model framework can be adjusted for comparing any set of maintenance options, allowing for a wider range of com-

parisons on all aspects of the track. Additional work is also needed in gathering validation data and refining the component-specific accident rates. Although much of the data used in this model was based on general industry data, a true validation will require data from actual railroad lines. Such data would allow the model to better represent the actual conditions of the railroad and be applicable to a wider range of scenarios.

ACKNOWLEDGMENTS

This research was supported by the National University Rail Center, a U.S. Department of Transportation Office of the Assistant Secretary for Research and Technology Tier 1 University Transportation Center, and the Association of American Railroads. The first author was also supported by an FHWA Dwight D. Eisenhower Transportation fellowship. The authors thank Andrew Scheppe of RailTEC for sharing his preliminary cross-tie accident analysis for inclusion in this paper.

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