

JRC2010-36029

BENEFIT-COST ANALYSIS OF INFRASTRUCTURE IMPROVEMENT FOR DERAILMENT PREVENTION

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ABSTRACT

U.S. railroad accident rates have declined substantially since the 1980s; however, further improvement in train safety remains an important objective of the railroad industry. In this paper, we describe a framework developed to assess the cost-effectiveness of railroad infrastructure improvement to reduce railroad train accidents.

Higher FRA track classes have been shown to be statistically correlated with lower accident rates, thereby indicating potential safety benefits. However, such infrastructure improvement also increases both capital and operating costs for track maintenance. We use accident data from the U.S. DOT Federal Railroad Administration (FRA) accident database and cost data from several recent U.S. railroad infrastructure maintenance projects presented in an FRA report to quantitatively evaluate the safety benefits and costs associated with infrastructure improvement decisions.

Our model is intended to consider the trade-off between reduced accident rates and increased costs in evaluating railroad risk reduction strategies and operational decisions. The benefit-cost analysis framework is illustrated by considering the upgrade of track class 3 to class 4 in a hypothetical case study.

INTRODUCTION

U.S. railroad train accident rates have declined substantially since the 1980s, due to major capital investments in infrastructure and equipment, improved safety design of railcars, employee training, and development and implementation of new technologies [1]. Nonetheless, further enhancement of transportation safety remains an important objective of the railroad industry.

There are various approaches to improving train safety and reducing railroad accident risk. Improving tank car safety design [2, 3], optimizing route selection [4, 5, 6], and upgrading infrastructure quality [7, 8] are among the risk reduction options. In this paper, we focused on infrastructure improvement and developed a framework to evaluate the cost-effectiveness of railroad track quality improvement as a means of reducing train accidents.

We aim to identify and quantify the derailment prevention benefits and financial impacts associated with track quality upgrade, and address the trade-off between reduced accident rates and increased track maintenance costs. The following analyses used accident data collected by the U.S. DOT Federal Railroad Administration (FRA) in the Railroad Accident/Incident Reporting System (RAIRS) database, focusing on all causes of derailments on Class I railroads on mainline track that occurred in the three-year period, 2006-2008 [9]. The cost data we used are from several recent U.S. railroad infrastructure maintenance projects summarized in a report by FRA [10].

METHODOLOGY

We developed an analytical approach to evaluate whether the costs of track quality improvement would be offset by the benefits of avoided railroad train derailments. The benefits of reducing derailments were calculated using data on the costs of railroad accidents, combined with data on the differences in track class-specific accident rates. The costs of infrastructure improvement are the additional maintenance costs for higher quality track. We used a Net Present Value (NPV) approach to perform the benefit-cost analysis because of the relatively long period of time over which the benefits and costs would accrue.

FRA specifies a set of track safety standards corresponding to railroad operating speeds, with higher speeds requiring higher track classes, and correspondingly more stringent engineering requirements (Table 1) [11]. Track class has been used in railroad safety and risk analyses as a proxy for track quality. Previous studies have shown that higher classes are statistically correlated with lower accident rates [12, 13, 14, 15]. In the absence of a better set of parameters for track quality, it is reasonable to consider FRA track class as a proxy variable for statistical estimation of accident probability. In this paper, infrastructure improvement is represented by upgrading a lower track class to a higher track class.

Table 1 FRA Track Class

Track Class	Maximum Freight Train Speed (mph) ¹
X&1	10
2	25
3	40
4	60
5	80
6	110 ²

We calculated the NPV of upgrading track class as the sum of the benefits of reduced cost of damage to track and equipment in derailments, minus the associated costs, calculated over the years during which the benefits and costs are expected to accrue. The monetary values of benefits and costs were discounted to constant (year 0) dollars. The equation used for NPV calculation is:

$$NPV = \sum_{i=0}^Y \frac{B_i(j,k) - C_i(j,k)}{(1+d)^i} \quad (1)$$

Where:

Y = time span over which NPV is calculated (years)

¹ FRA requirements limit train speeds to less than 50 mph in non-signalized territory.

² Although FRA track class safety standards allow speeds up to 110 mph on class 6 track, FRA traffic control regulations limit train speeds to less than 80 mph on most U.S. trackage.

B_i = derailment reduction benefits of track class upgrade in year i

C_i = costs of track class upgrade in year i

d = annual discount rate

j,k = upgrade track from class j to class k

We assumed that infrastructure upgrades occurred in year 0 and that derailment reduction benefits and costs begin to accrue in the following year, so that $B_0 = 0$ and $C_0 = 0$. We also assumed that the principal cost in successive years is the cost of maintaining the higher-class track, minus the maintenance cost for the current track class. Several other simplifying assumptions were made as follows. First, we assumed constant track class-specific railroad train accident rates over the time horizon of the analysis. Historically, railroad accident rates declined rapidly following deregulation in the 1980s and then leveled off in the 1990s and early 2000s, and began to decline again in the mid 2000s. In light of these historical trends an approach that allows for varying future accident rate should ultimately be incorporated into the framework described here. Second, we assumed that the cost of track maintenance would remain constant; however, new developments in track maintenance technology could reduce unit costs in the future. Finally, we used a constant annual discount rate in the NPV calculation. If any of these assumptions needs to be changed, the model could be revised to account for them. The following discussion of benefit estimation, cost estimation, and NPV calculation describe how we estimated the factors in equation 1.

BENEFIT ESTIMATION

The derailment reduction benefits of track class upgrade are the expected average savings associated with avoided train accidents over the analysis period. To estimate the magnitude of these savings, past accidents were reviewed. The FRA requires railroads to submit detailed reports of all accidents that exceed a specified monetary threshold for damage to track, structures, equipment and signals [16]. These reports are compiled in the Railroad Accident/Incident Reporting System (RAIRS) database and FRA publishes an annual report containing a variety of summary statistics. The database is available at the website of the FRA Office of Safety Analysis. The accident analyses described in this paper are based on data downloaded from the FRA website for the three year period, 2006-2008. Throughout this paper, accident consequence costs include the monetary values of track and equipment damages due to train accidents. The formulae for the calculation of derailment reduction benefits associated with infrastructure improvement are:

$$B_0(j, k) = R_{0j} - R_{0k} \quad (2)$$

$$R_{0j} = P_j \times C_{0j} \quad (3)$$

Where:

$B_0(j, k)$ = derailment reduction benefits of upgrading track class j to class k in 2008 dollars (\$/million ton-miles)
 R_{0j} = accident risk on track class j in 2008 dollars (\$/million ton-miles)
 P_j = accident rate on track class j (accidents/million ton-miles)
 C_{0j} = consequence cost per accident on track class j in 2008 dollars (\$)

Anderson and Barkan developed estimates of Class I railroads' mainline freight-train accident rates based on the FRA safety statistics [15]. In the analyses described here we used their estimates of average rates for all causes of mainline derailments on Class I railroads, and converted the derailment rate in terms of per billion ton miles assuming average train weight of 6,259 tons [17].

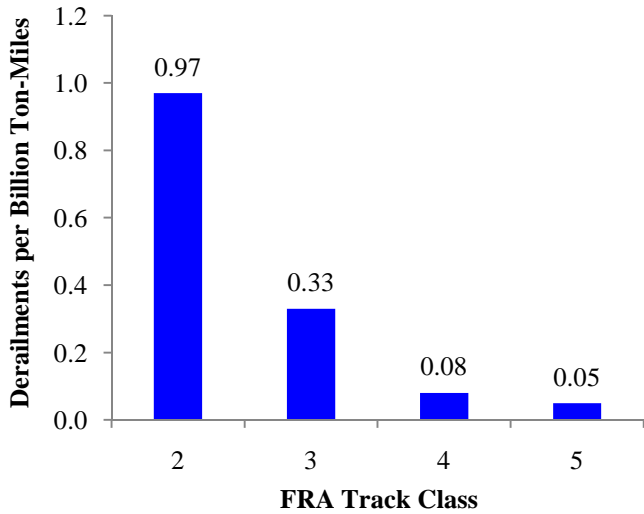


Figure 1 Class I mainline derailment rates

In this paper, we focused on freight train accidents and excluded passenger data from the analysis. The average consequence costs per accident C_{ij} consist of track and equipment damages, obtained from the FRA accident database (2006-2008). When the data are summarized, it is evident that the average consequence costs are affected by the distribution of FRA track classes (Table 2). Track class 5 has the highest average consequence cost per derailment, while track class 1 has the lowest.

Table 2 Average Consequences per Mainline Derailment (2008 Dollars)

Track Class	Number of Derailments	Track & Equipment Damage (thousand \$)
1	161	105
2	182	262
3	229	362
4	437	483
5	129	530
Average	228	375

Train derailment risk was calculated by multiplying track class-specific derailment rate times average consequence cost per derailment (Figure 2). As such, derailment risk is the compound result of derailment probability and associated consequences. Higher track classes have lower derailment rates but may have more severe consequences due to higher operating speeds. The net result is that track class 1 has the highest derailment risk (\$814 per million ton-miles), whereas the risk on track class 5 is the lowest, which is estimated to be \$27 per million ton-miles. It is estimated that approximately 95% of freight traffic (in terms of gross ton-miles) over U.S. rail network is transported on track classes 3, 4 & 5 (unpublished data from the University of Illinois). Therefore, in this paper we focused on investigating the cost-effectiveness of the upgrades of these track classes.

The benefit of infrastructure improvement is derived from reduced derailment risk. We calculated the benefit due to derailment reduction for each pair-wise combination of track-class upgrades (Table 3) For instance, if a segment of class 3 track is upgraded to class 4, the risk reduction is estimated to be \$77 per million ton-miles (\$118 - \$41 = \$77). The derailment reduction benefit of track class upgrade was calculated and presented in Table 3. The benefit of track condition improvement was assessed in 2008 dollars, and we assumed a 3% average annual inflation rate. The benefit occurring in year i can be calculated as:

$$B_i(j, k) = B_0(j, k) \times (1+3\%)^i \quad (4)$$

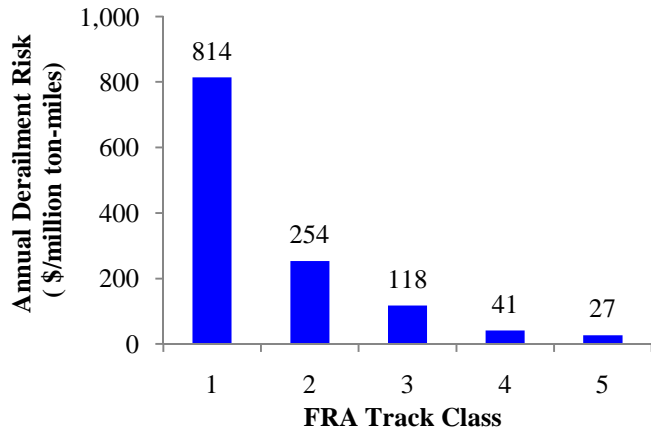


Figure 2 Track class-specific derailment risk (2008 dollars)

Table 3 Annual Derailment Reduction Benefit of Track Class Upgrade $B_0(j, k)$ (\$ per Million Ton-Miles)

	Class 3	Class 4	Class 5
Class 3	0	77	91
Class 4		0	14
Class 5			0

COST ESTIMATION

The costs of upgrading infrastructure are due to the additional track maintenance expenses for higher track classes and are based on a study done for FRA by Zarembski and Resor [10]. U.S. railroads use a combination of renewal and ordinary maintenance techniques to maintain their infrastructure [18, 19]. Capitalized renewal maintenance typically involves replacement of relatively large quantities of track structure materials and components. By contrast, ordinary maintenance is charged to operating expense, and includes frequent inspections, drainage correction, rail lubrication and grinding, ballast tamping and minor repairs of track and structures. The cost of both renewal and ordinary maintenance expenses are affected by FRA track class, traffic density, type of tie, and track curvature. In the analysis presented here, we used data for mainline tangent track with wood ties as an example to describe the cost estimation process. Total track maintenance (renewal plus ordinary) is modeled as a function of traffic density for each track class given track curvature and tie type:

$$M_{0j} = \alpha_{0j} / X + \beta_{0j} \quad (5)$$

Where:

M_{0j} = annual total track maintenance cost on track class j in 2008 dollars (\$/million ton-miles)

α = fixed cost (\$/track mile)

β = marginal variable cost (\$/million ton-miles)

X = traffic density (million tons)

Estimated average fixed and marginal variable costs were presented in Table 4. The FRA report we used does not provide information on track classes 1, 2 and 3; therefore, their coefficients (α_0 and β_0) were extrapolated from track classes 4, 5 and 6 (class 6 track was not considered in this paper).

Table 4 Fixed and Marginal Variable Maintenance Cost (2008 Dollars)

Track Class	α_0 (\$/track mile)	β_0 (\$/million ton-miles)
1	9,018	319
2	10,290	431
3	11,561	544
4	12,904	663
5	13,963	753

An infrastructure index (MOW-RCR) was developed from components of the AAR Railroad Cost Recovery Index (AAR-RCR) using the methodology developed by Grimes [18, 19]. MOW-RCR was used to adjust maintenance costs incurring at various years in terms of base year prices. Grimes developed an approach to calculate the MOW-RCR [18, 19]. A regression analysis of recent MOW-RCR indicates that MOW-RCR varied linearly over the interval 1991-2006 (Figure 3) and can be described using the equation:

$$I_i = 5.067 \times i + 239.136 \quad (6)$$

Where:

I_i = MOW-RCR in year i ($i = 0$ for year 2008)

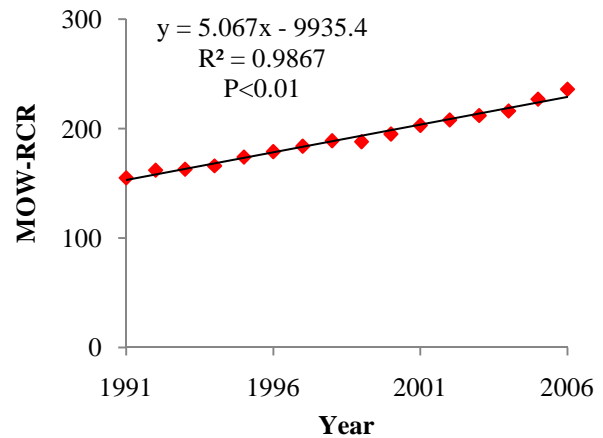


Figure 3 Relationship between MOW-RCR and year

The cost of track class upgrade in year i can be calculated as:

$$C_i(j,k) = (M_{0k} - M_{0j}) \times I_i / I_0 \quad (7)$$

Where:

$C_i(j,k)$ = cost of upgrading class j to class k in year i
(\$/million ton-miles)

I_i = MOW-RCR in year i

I_0 = MOW-RCR in year 0

(base year is 2008; $I_0=239.136$)

As such, the cost estimation is extended to be:

$$C_i(j, k) = [(\alpha_{0k} - \alpha_{0j}) / X + (\beta_{0k} - \beta_{0j})] \times (0.021 \times i + 1) \quad (8)$$

The values of α and β can be looked up in Table 4 and i is the year index assuming that 2008 is year 0.

CASE STUDY

We conducted a case study in which we increased the track class of a segment of class 3 track to class 4. This track segment is composed of tangent track with wood ties and has homogenous annual freight traffic density of 100MGT (million gross tons). We used equations (1) to (8) to calculate the cumulative benefit, cumulative cost and NPV derived from infrastructure improvement (Table 5). The analysis period was 30 years with an annual discount rate of 7% and 2008 as the base year.

Table 5 NPV of Infrastructure Improvement

Year	Cumulative Benefit (\$/million ton-miles)	Cumulative Cost (\$/million ton-miles)	NPV (\$/million ton-miles)
5	344	578	-234
10	628	1,031	-403
15	863	1,383	-520
20	1,057	1,655	-598
25	1,218	1,864	-646
30	1,351	2,023	-672

The NPV of track class upgrade equals cumulative benefit minus cumulative cost given traffic density. In this case study, the NPV is approximately -\$672 per million ton-miles at the end of 30 years. This suggests that given the data and assumptions used in this analysis the benefits due to derailment reduction from track class upgrade do not, by themselves, outweigh the increase in costs. However, it should be noted that there are other associated costs and benefits that are not considered here. For instance, we did not take into account other forms of safety benefits due to avoided train derailments, such as reduced fatalities and injuries, reduced lading loss and damage and reduced liability. In addition, we did not consider the business benefits resulting from track class upgrade, including reduced train delay time and increased transportation

capacities. These factors are affected by traffic level and operations. The extent of the benefits of derailment prevention will also be affected by the presence, volume, type and packaging practices of hazardous materials on a line. These benefits of derailment prevention are more difficult to estimate but are part of the longer-term objectives for this research.

Costs due to initial track structure retrofitting vary among railroads as well due to a variety of geographic factors and were not included in the model. Decision makers would need to incorporate figures on both costs and benefits appropriate to their railroad and the particular conditions of a line to properly analyze the cost-effectiveness for their specific operations and infrastructure conditions.

Calculation of NPV is subject to a variety of uncertainties such as traffic density and the estimation of benefit and cost. We conducted a sensitivity analysis to examine how NPV varies with these factors.

SENSITIVITY ANALYSIS

In this section, we describe a sensitivity analysis in which we investigated the effects of traffic density and benefit-cost estimation on the NPV calculation. NPV is subject to other uncertainties regarding calculation method and input information, but these factors are beyond the scope of this study.

First, we examined how track density levels affect the assessment of benefit, cost and NPV (Figure 4). Benefit is traffic independent and is fixed at \$1,351 per million ton-miles when the analysis time is 30 years and annual discount rate is 7%. By contrast, cost decreases with increased traffic densities, falling from \$5,901 per million ton-miles at a traffic level of 5MGT, to \$1,993 per million ton-miles when traffic density rises to 120MGT. Unit costs are reduced when the fixed cost is distributed over a larger amount of traffic. Consequently, *ceteris paribus*, higher traffic densities result in higher NPV, indicating that track condition improvement is likely to be more cost-justified under higher traffic densities than low, reflecting the economies of density for railroad track maintenance [19].

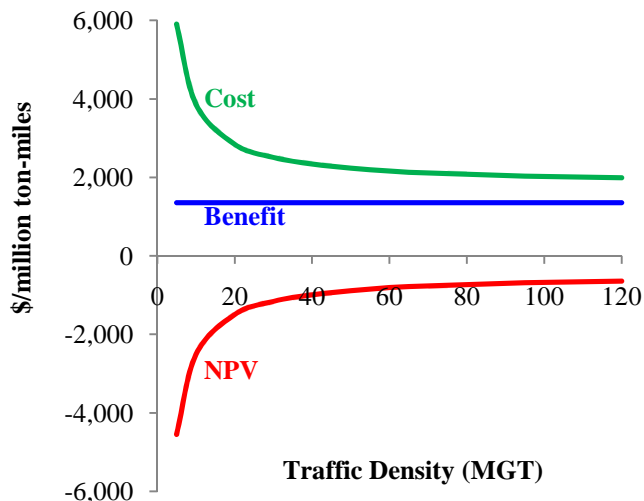


Figure 4 Effect of traffic density on NPV (upgrade class 3 to class 4)

The analysis indicated that NPV was negative over the entire range of traffic densities considered, indicating that the benefit of the avoided cost due to track and equipment damages does not by itself offset the increased financial impacts of infrastructure upgrade. In order to better understand this result, we analyzed how much higher the benefit would have to be, or how much lower the costs, in order to yield a positive NPV. We identified the minimum benefit and cost multipliers μ and $1/\mu$, respectively, that would result in positive NPV (Figure 5). It shows that higher traffic density has a lower benefit-cost multiplier. When traffic density is 5MGT, changes in benefit or cost would need to be approximately five times the estimated benefit and cost, to cost-justify infrastructure upgrade, whereas at 120MGT, the benefit would have to be about one and a half times higher to result in a positive NPV.

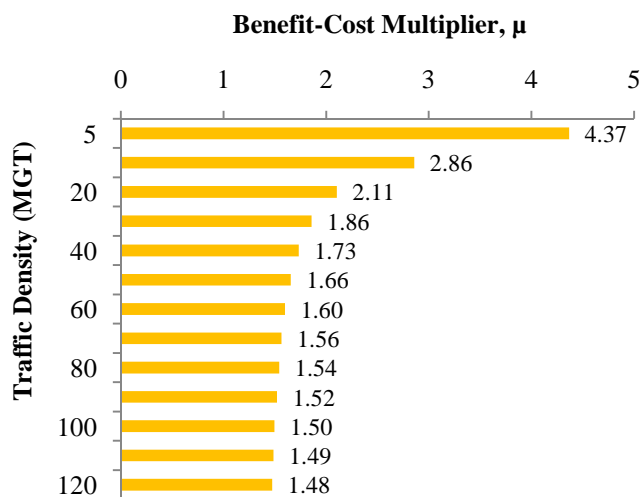


Figure 5 Minimum Benefit-Cost Multiplier to Attain Positive NPV

DISCUSSION

This paper describes a framework to address the cost-effectiveness of track-class upgrade with respect to railroad derailments. The purpose of the paper is to present the basic approach and to illustrate it using representative data to gain some insight regarding the relative costs and benefits of this approach to reducing railroad accident risk and their effect on NPV. As illustrated in the sensitivity analyses, variations in certain input parameters result in large changes in NPV. Decision makers wishing to use this methodology would need to incorporate the benefit and cost information suitable to the particular line segment and questions of interest to them.

The optimal infrastructure improvement strategy will also be affected by budget and engineering constraints, projected transportation demand, and other factors. In this paper, our focus was on evaluating the cost-effectiveness of infrastructure upgrade as a means of reducing derailment occurrence and ultimately risk. Although cost-effectiveness is a key concern in the decision making process, it is not the only one and final decisions will be based on multiple, and sometimes conflicting criteria.

CONCLUSION

In this paper, we investigate the benefits and financial impacts of railroad infrastructure improvement and present a basic analytical framework to evaluate the cost-effectiveness of this approach to derailment prevention. A sensitivity analysis was performed to examine how NPV varies with traffic density and the estimation of benefit and cost. The sensitivity analysis showed that track class upgrade is more cost-justified given higher traffic density. It also provided insight into how much higher the benefits would need to be, or how much lower the costs, for this approach to derailment prevention to be cost effective. A variety of other factors also affect the decision to increase FRA track class and all need to be considered when making decisions regarding infrastructure improvement.

FUTURE RESEARCH

Identifying and quantifying other benefits and costs associated with infrastructure improvement is the next step of this research. Other possible benefits of avoided train accidents include reductions in: fatalities and injuries due to train accidents, train delay cost, lading loss and damage, hazardous materials impacts, liability, and increased transit speed and line capacity. More predictive, up-to-date information on capital and ordinary maintenance costs for track structure upgrade should also be developed.

The ultimate goal is to incorporate this model into a larger, unified risk analysis framework that would enable objective assessment of infrastructure upgrade in comparison to other

approaches to risk reduction, such as rail equipment and operational changes.

ACKNOWLEDGMENTS

The authors are grateful to the following individuals from the Railroad Engineering Program at University of Illinois at Urbana-Champaign for their assistance on this paper: Athaphon Kawprasert and Amanda Koenig. We also appreciate the useful comments from the anonymous reviewer.

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