Benefit-Cost Analysis of Heavy Haul Railway Track Upgrade for Safety and Efficiency

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Summary: Upgrading track quality offers potential safety and service quality benefits because it can reduce both derailment rate and transportation time. However track upgrades are costly and increase capital and operating expense for upgrade and maintenance. A preliminary model was developed to estimate the various safety and performance benefits, the extra costs, and the net present value (NPV) associated with track class upgrade. The analysis accounts for traffic volume and track information. Different track upgrade strategies require correspondingly different levels of traffic to cost-justify the track upgrade decision. The sensitivity of the NPV results to discount rate and track upgrade cost as a function of traffic density was also analyzed.

1. Introduction

Derailments are the most common type of train accident on North American heavy-haul railroads and reducing their occurrence and severity is an ongoing objective of both industry and government. Upgrading track quality is one possible derailment prevention strategy [1, 2, 3, 4, 5]. The United States Department of Transportation, Federal Railroad Administration (FRA) defines track quality standards or "track classes" required to operate freight and passenger trains at different maximum speeds. There are five principal track classes commonly used by heavy-haul freight railroads in the U.S. ranging from class 1 with the lowest maximum speed, to class 5 with the highest. These classes include specifications for track structure, geometry, and inspection frequency and method, with more stringent requirements for higher track classes. FRA track classes have also been shown to be statistically correlated with derailment rate, with higher classes having lower rates [6, 7], thereby indicating potential safety benefits irrespective of operating speed. Furthermore, the higher operating speeds associated with higher track classes imply economic and service-quality benefits due to reduced running times and increased line capacity. However, construction and maintenance of higher FRA track classes also results in higher capital and operating expense. Previously published studies have not simultaneously considered the safety effects, performance benefits and costs associated with different FRA track classes. In this paper we describe initial development of an economic model to enable benefit-cost analyses of track class upgrades.

2. Methodology for Benefit-Cost Analysis

A net present value (NPV) approach was developed to evaluate whether the costs of track class upgrade would be offset by the benefits of avoided train derailments and reduced run time on higher track classes. The NPV of upgrading track class was calculated as the sum of the reduced costs of damage in derailments plus the benefits of reduced running time, minus the associated costs, over the time span they are expected to accrue. The monetary values of benefits and costs were discounted to constant (year 0) dollars and Equation (1) was used to calculate the NPV.

$$NPV=\sum_{i=0}^{Y}\frac{B_i(j,k)-C_i(j,k)}{(1+d)^i}-C_0 \tag{1}$$

where:

- Y = time span over which NPV is calculated (years)
- B_i = benefits of track class upgrade in year i
- C_i = costs of track class upgrade in year i
- C_0 = initial track upgrade cost in year 0
- 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 the benefits begin to accrue in the following year, so that B_0 = 0. It was also assumed that the principal marginal cost in successive years is the cost of maintenance and periodic renewal of the higher-class track, minus the same costs if there was no upgrade. Several other simplifying assumptions were made as follows. First, track-class-specific train derailment rates over the analysis period were held constant. Historically, U.S. railroad accident rates declined rapidly following deregulation in the 1980s and then leveled off in the 1990s and early 2000s, with a more modest decline again beginning 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, the cost of track maintenance was assumed to remain constant; however, new developments in track maintenance technology could reduce unit costs, or conversely, increased material prices could increase unit costs. Finally, we assumed a constant discount rate in the NPV calculation. Modification of any of these assumptions can be accommodated in a revised version of the model presented here. The following sections describe how the benefits and costs used in the NPV calculation were estimated.

3. Benefit Estimation

3.1 Derailment Prevention by Track Class Upgrade

The derailment reduction benefits of track class upgrade are the expected average savings associated with avoided train accidents over the analysis period. Past accidents were reviewed to estimate the magnitude of these savings. FRA regulations require railroads to submit detailed reports of train accidents that exceed a specified monetary threshold of damages to track, structures, equipment and signals. These reports are compiled in the Railroad Accident/Incident Reporting System (RAIRS) database, which is available on the website of the FRA Office of Safety Analysis [8]. The accident analyses described in this paper are based on FRA-reportable, Class I railroad mainline derailments from 2006 to 2008. Derailment consequence costs are calculated using the monetary value of the damages reported to FRA as described above. The formulae for the calculation of derailment reduction benefits due to track class upgrade are:

$$B(j, k) = R_j - R_k \quad (2)$$

$$R_j = P_j \times M_j \times C_j \quad (3)$$

where:

$B(j, k)$ = derailment reduction benefits of upgrading track class j to class k in 2008 dollars ($)
R_j = derailment risk on track class j in 2008 dollars ($)
P_j = derailment rate on track class j (derailments/million gross ton-miles)
M_j = traffic exposure on track class j (million gross ton-miles)
C_j = consequence cost per derailment on track class j in 2008 dollars ($)

Anderson and Barkan developed estimates of Class I railroads' mainline freight-train accident rates based on FRA safety data [7]. We used their estimates of average rates for all causes of mainline derailments on Class I railroads and calculated the derailment rate per billion ton-miles assuming an average train weight of 6,441 tons [9]. Higher track classes have been shown to be statistically correlated with lower derailment rates [6, 7] (Figure 1)[1], enabling quantification of

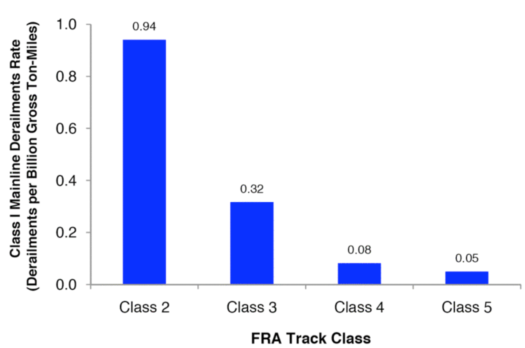

Figure 1. Class I mainline freight-train derailment rates by FRA track class [7]

[1] Track class 1 is excluded from most of the analyses presented here due to minimal traffic on this track class over the national freight rail network (<1%)

the potential safety benefit of track class upgrade. The average consequence per derailment, C_{ij} consists of the damage costs reported to the FRA accident/incident database, 2006-2008 and is affected by the distribution of FRA track classes (Table 1).

Table 1. Average Derailment Consequence Costs, Class I Mainline Freight-Train, 2006-2008 (2008 Dollars)

Track Class	Number of Derailments	Average Track & Equipment Damage per Derailment ($)	Standard Error ($)
1	145	114,093	13,731
2	198	272,231	23,041
3	224	353,570	29,420
4	439	509,247	32,443
5	124	557,797	71,377
Total	1,130	391,479	17,071

Track class 5 has the highest average consequence cost per derailment, while track class 1 has the lowest. The difference is due to the higher average derailment speed and consequent greater severity of derailments on higher track classes [10]. The average cost per derailment on Class I railroad mainlines was $391,479. Higher track classes were also shown to have a larger standard error, implying a greater range of accident severity. This is probably due to the wider range of accident speeds possible on higher track classes. Train derailment risk was calculated by multiplying track-class-specific derailment rate by track-class-specific average consequence cost per derailment (Figure 2). Derailment risk in this context is defined as derailment probability multiplied by derailment cost. Higher track classes have lower derailment rates but more severe consequences. The lower rates more than offset the higher average consequences on higher track classes, with the net result that class 2 track has the highest derailment risk at $256 per million ton-miles, and class 5 the lowest, at $28 per million ton-miles.

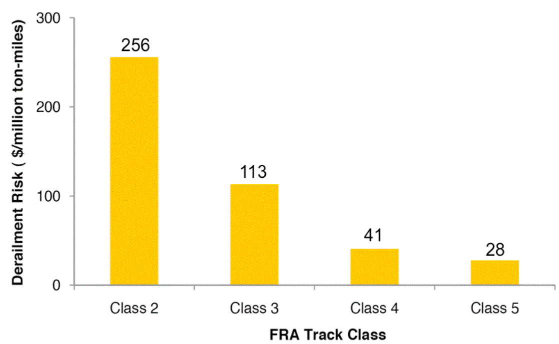

Figure 2. Track-class-specific Class I mainline freight-train derailment risk

The benefit due to derailment reduction was calculated for each pair-wise combination of track class upgrade (Table 2). For example, if a segment of class 3 track is upgraded to class 4, the estimated reduction in risk is $72 per million ton-miles ($113 - $41 = $72).

Table 2. Derailment Reduction Benefit of Track Class Upgrade ($ per Million Ton-Miles)

	Class 2	Class 3	Class 4	Class 5
Class 2	0	143	215	228
Class 3		0	72	85
Class 4			0	13
Class 5				0

3.2 Run Time Reduction on Higher Track Classes

Lai et al. [11] developed a relationship between run time and traffic volume using Rail Traffic Controller (RTC) simulation software for a hypothetical 124-mile route representing a typical midwestern U.S. single-track rail line (Figure 3).

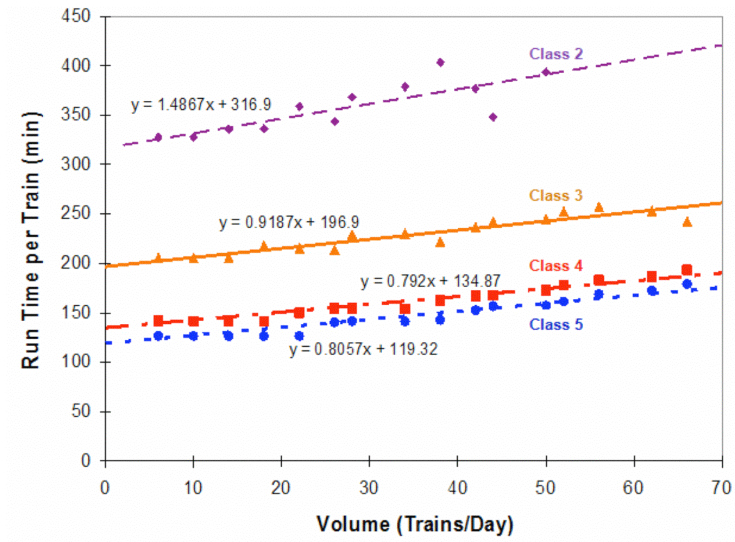

Figure 3. Unit run time as a function of traffic volume and FRA track class (adapted from [11])

We assumed the same, previously cited AAR statistic for average train weight of 6,441 tons [9] and one year of operation. The relationship between run time per train and traffic volume for the 124-mile route was used to calculate total annual run time versus traffic density (Figure 4A).

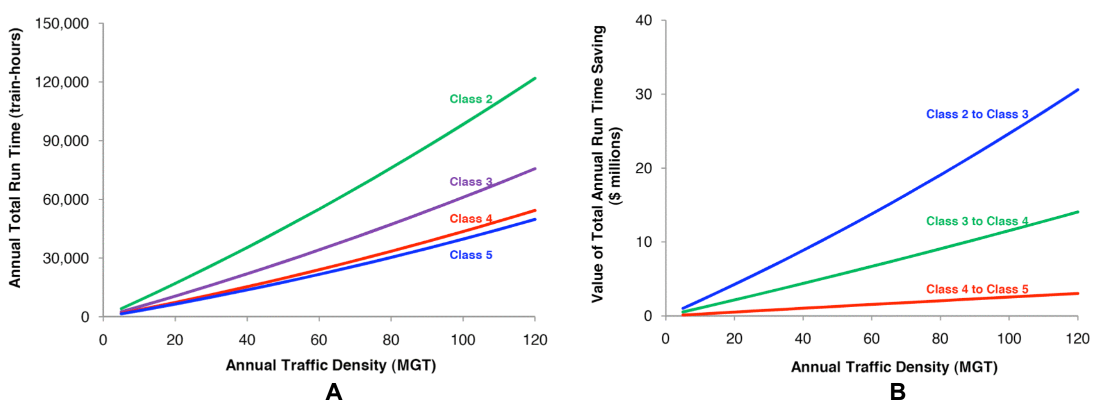

Figure 4. (A) Relationship between annual traffic density and total run annual time and (B) estimated economic value of run time savings

The RTC simulation results show that higher track classes have shorter run times given the same traffic density [11]. The economic value of these shorter run times were calculated as the product of the saved run time multiplied by the value of unit run time. We assumed the latter to be equal to train delay cost per unit time. A number of studies have attempted to quantify train delay cost. These estimates are affected by a variety of factors including when the study was done, train type, traffic density and other factors [12, 13, 14, 15, 16]. We used a recent estimate by Schlake et al of $662 per train-hour for bulk-freight trains [16] to estimate the value of run time savings for various track class upgrades and traffic densities on our hypothetical line (Figure 4B). This figure includes all the railroad's costs as well as an estimated average cost of lading delay.

4. Cost Estimation

The extra cost of upgrading track infrastructure includes an initial track upgrade cost and ongoing marginal increases in ordinary maintenance and renewal maintenance expenses. The initial expense accounts for capital costs for upgrading to new rail, crossties, ballast, surfacing and other related work. Ongoing maintenance costs include ordinary track maintenance cost (operating cost) and cyclic renewal track maintenance cost (capital cost).

4.1 Track Upgrade Cost

Initial track upgrade costs vary depending on infrastructure conditions, geological and geographic characteristics, labor and equipment costs and specific track upgrade activities. A number of studies have been conducted on estimation of these costs [1, 17, 18, 19, 20, 21, 22]. Based on review of this work, we assumed $600,000 per mile for the initial track upgrade cost for all track classes.

4.2 Track Maintenance Cost

U.S. railroads use a combination of renewal and ordinary maintenance techniques to maintain their infrastructure [23, 24]. Capitalized renewal maintenance typically consists of the replacement of relatively large quantities of track structure materials and components. By contrast, ordinary maintenance is charged to operating expense, and involves frequent inspections, rail lubrication and grinding, ballast tamping and minor repairs of track and structures. Both renewal and ordinary maintenance expenses are affected by FRA track class, traffic density, type of crosstie, and track curvature. In our analysis we used maintenance cost data derived from a study done for FRA [25]. We assumed mainline, tangent or light curvature track with wood crossties. Total track maintenance (renewal plus ordinary) is modeled as a function of traffic density for each track class as follows:

$$M_j = \alpha_j + \beta_j \times M \tag{4}$$

where:

M_j = annual total track maintenance cost on track class j in 2008 dollars ($/track mile)

α_j = fixed track maintenance cost on track class j ($/track mile)

β_j = marginal variable track maintenance cost on track class j ($/million ton-miles)

M = annual traffic density (MGT)

The estimated average fixed track maintenance costs ranged from $10,252 per mile for Class 2 track, to $13,911 per mile for Class 5 track, with corresponding marginal variable costs of $431 per million ton-miles, to $751 per million ton-miles, respectively (Table 3).

Table 3. Fixed and Variable Track Maintenance Cost, Tangent or Light Curvature Rail and Wood Crosstiefor Different FRA Track Classes* (2008 Dollars)

Track Class	α_0 ($/track mile)	β_0 ($/million ton-miles)
2	10,252	431
3	11,518	542
4	12,856	661
5	13,911	751

* The Zarembski & Resor report [25] did not provide information on track classes 2 and 3; therefore, their coefficients (α_0 and β_0) were extrapolated from track classes 4, 5 and 6.

5. NPV of Track Class Upgrade

We considered the same 124-mile single-track route described above, operated with predominantly bulk traffic to conduct the economic analyses. Equations (1) to (4) were used to calculate the cumulative benefits, costs and NPV. We evaluated track class upgrades on the route with annual traffic densities ranging from 5 MGT to 120 MGT and a track life of 25 years using 2008 monetary values for the base year. We used 10% as the discount rate based on the International Heavy Haul Association (IHHA) recommendation for life cycle cost analysis of railroad infrastructure [26]. Three track class upgrade scenarios were considered: upgrading class 2 to 3, class 3 to 4 and class 4 to 5 (Figure 5). In all three scenarios there was a positive relationship between traffic volume and NPV, but the strength of this relationship varied. Upgrading from class 2 to 3 yielded a positive NPV above approximately 40 MGT and upgrading from class 3 to 4 was positive above 80 MGT. Upgrading from class 4 to 5 did not yield a positive NPV at any of the traffic levels considered.

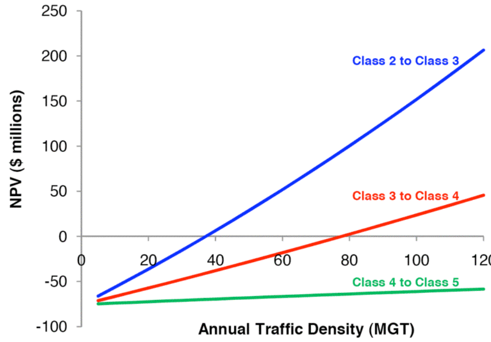

Figure 5. NPV of different track class upgrades as a function of traffic density

The higher traffic threshold required for a positive NPV for the higher track classes is not surprising. Maintenance of these track classes is more costly and thus a higher return is required to justify the investment. However, the meaning of the results for the lower track classes is less clear. U.S. railroads routinely maintain track with lower traffic levels to higher standards than the NPV analysis would suggest is cost effective. This indicates that other transportation, budget and engineering factors are not being considered in this preliminary analysis. We are continuing this research with the objective of developing a more complete understanding all the factors affecting the economics of track class decisions, but in order to gain further insight into the question we conducted two additional sensitivity analyses.

6. Sensitivity Analysis

Two assumptions in our work that could affect the results are the discount rate and track class upgrade cost, consequently we conducted a sensitivity analysis of the effects of these two parameters on the results using the class 3 to class 4 track upgrade as an example.

6.1 Discount Rate

NPV results are critically affected by discount rate. Different values for this parameter may be used depending on the type of organization conducting a project and the nature of that project [27, 28, 29]. In our base case analysis we used the 10% discount rate recommended by IHHA [26]. It is evident that use of different discount rates has a substantial impact on the results (Figure 6A). A 15% discount rate resulted in a positive NPV at only the very highest traffic levels considered. On the other hand, use of a 5% discount rate, such as might be used in public projects, substantially increased the range of traffic volume over which the NPV was positive.

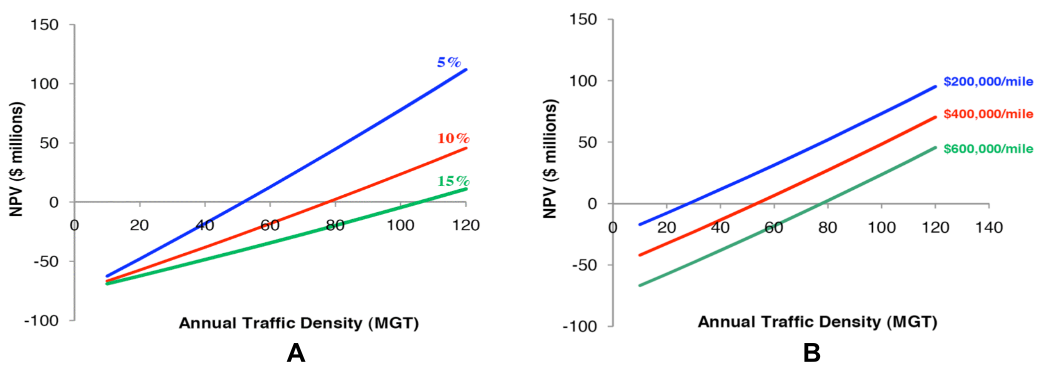

Figure 6. Sensitivity analyses for upgrading class 3 to 4 track affected by (A) discount rate and (B) track upgrade cost

6.2 Track Upgrade Cost

We also conducted a sensitivity analysis of track upgrade cost. In the base case analysis we used $600,000 per mile for all track classes. It is reasonable to consider whether lower track class upgrades have lower initial upgrade costs. When the cost was reduced to $400,000 or $200,000, a much lower traffic threshold was required for a positive NPV (Figure 6B).

7. Conclusions and Future Research

We developed a basic analytical framework to quantitatively evaluate the benefits and costs of upgrading FRA track classes. Upgrading track class is expected to reduce derailment rate and run time, but it will also incur additional costs for the initial upgrade, and higher ongoing capital and operating cost for track maintenance. Upgrading track class is more cost-justified for lines with higher traffic densities because both the safety and operating benefits are greater. A sensitivity analysis indicated that a lower discount rate and/or track upgrade cost results in a lower traffic threshold required to yield a positive NPV. The preliminary model described here is a first step toward development of a more comprehensive analytical approach to optimization of track investment strategies accounting for the multiple trade-offs in the life cycle of railway infrastructure construction, track degradation, maintenance standards and operational requirements. Accident-cause-specific cost and safety benefit functions are also needed to better understand the relationship between safety and infrastructure quality. Finally, infrastructure improvement needs to be considered simultaneously with various other safety and risk reduction strategies as part of an integrated risk management framework. The objective of this is to enable better decision-making regarding the most cost-effective set of risk reduction strategies to choose given various constraints.

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