ANALYTICAL METHOD TO CALCULATE RISK-BASED TRACK SEPARATION DISTANCES FOR HIGH SPEED TRACKS IN FREIGHT CORRIDORS

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ABSTRACT
As high speed rail is developed in the United States, there is an expectation that at least some of the high speed tracks will be implemented within proximity of existing freight rail corridors. Although separate assets, right-of-way constraints to fit both high speed tracks and freight tracks within proximity of such existing corridors will likely lead to high speed tracks being in proximity to freight tracks.

When a freight train derails, there is the probability of dispersion of the equipment outwards from the centerline of the freight track. If a high speed track is in proximity to the freight track, there is risk of the high speed track being fouled by freight equipment. As expected, the probability of such track fouling decreases with increased track separation distance between the two tracks.

The authors present a robust analytical approach to understand and manage the risk of high speed track fouling from freight derailments. Mitigations to reduce the risk of derailment and track fouling are applied to achieve and manage a reasonable risk level, and implement cost effective risk management policies.

INTRODUCTION
This paper presents a robust analytical approach and results to understand the safety implications of track separation distances between freight and high-speed tracks in proximity to one another, and how mitigations can be applied to achieve and manage a reasonable risk level.

The objective of the analysis is to understand the risk probability of specific track separation distances and identify cost effective mitigation measures that can be applied to corridors where high speed rail tracks are in proximity to freight tracks.

The analysis estimates the probability of a freight train derailment fouling a high-speed track due to dispersion of freight rolling stock equipment; and, it estimates the reduction in probability through the application of specific risk mitigation measures.

The risk probability is influenced by the dispersion distance probability of derailed freight equipment traveling from the freight track centerline and fouling a high-speed track, and the potential to reduce this probability by means of mitigation measures.

The analysis uses three key datasets, which include:
- Data from a National Transportation Safety Board (NTSB) study that was performed during the late 1970’s and early 1980’s to investigate tank car safety and storage of vehicles in sidings.
- FRA Reportable Incident data from Class 1 Railroads
- Track utilization in annual train miles for specific FRA classes of track.
The analysis approach follows this order:
1. Estimate the dispersion distance Probability Density Function (PDF) based on available data collected from previously investigated derailment incidences by the NTSB.
2. Calculate the derailment rates on specific FRA classes of track by train-miles, given that train-miles are a measure of traffic density, and FRA track classes provide a measure of quality of track.
3. Estimate the probability of track fouling occurring based upon specific track separation distances.
4. Estimate the reduction in probability of track fouling occurring by the implementation of mitigation techniques, as applied to tracks of specific separation distance.

In this approach, both derailment prevention and derailment barrier mitigation techniques are used. Collectively, these are the risk mitigation measures that can be deployed.

KEY ASSUMPTIONS

Some key assumptions are made in the development of this approach. These are:

- It is assumed that the cause of a train derailment and the dispersion of the rolling stock equipment are independent. In other words, once a train leaves the track the equipment will disperse and the reason it left the track is no longer relevant. This is important because train derailments are caused by a multitude of reasons, and often the confluence of several factors. These vary widely from derailment to derailment.
- The incident of a train-to-train collision would be expected to influence dispersion, but the authors assume that the implementation of the high-speed railway will be after the implementation of Positive Train Control which is legislated and will be designed to eliminate the possibility of such collisions.
- While it is assumed that curvature and derailments at special track work would likely have some influence on the dispersion probability, the influence of this was beyond the scope of this initial analysis. Future studies should consider this.
- It is assumed that the dispersion PDF is applicable for all train speeds. This assumption appears to be valid based upon the statistical analysis on the NTSB data conducted by English, et.al. [1], in which there was little statistical correlation between maximum lateral dispersion and train trailing tons, which is an indicator of train make-up. The NTSB data may be somewhat conservative, in that few minor accidents would have been included [2].
- It is assumed that the dispersion PDF is applicable for all train types that will operate on freight tracks in proximity to high-speed tracks. This is important because freight tracks carry many different types and make-ups of freight traffic. There is evidence to indicate that this assumption is valid. The statistical analysis on the NTSB data conducted by English, et.al.[1], found little statistical correlation between maximum lateral dispersion and train trailing tons, which is an indicator of train make-up. The NTSB data may be somewhat conservative, in that few minor accidents would have been included [2].
- It is assumed that the dispersion PDF is applicable for current freight car types operating on the railroad. It is assumed that the vehicles operating on the railroad today are very similar in design to those operating when the NTSB data was collected. Data from the AAR shows that at the end of year 2008, 66 percent of locomotives had nine or more years in service, and 30 percent had greater than 23 years in service [3]. Data from the AAR also showed that over the 10-year period from 1999 to 2008, an average of 3.8 percent of the car fleet was replaced per year. Using this average, there would have been a full turnover of the car fleet in the 30+ years since the NTSB data collected. However, many of the cars replaced are assumed to have been heavily used gondolas and hoppers which represent well over 50 percent of the fleet. The designs of these car types have not substantially changed over the years since the NTSB data was collected. It is noted that double-stack container and auto-rack freight traffic has increased over the past 30 years, and may be under-represented in the NTSB dataset. Future analyses will be helpful to fill this gap.
- The shape of the dispersion PDF curve reflects a gamma distribution. As such, a statistically valid probability analysis is assumed. The data analyzed by English, et. al. [1], indicate this to be the case, as does the analysis performed by the authors.
- It is assumed that the implementation of the Staggers Act in 1982 has no influence on the dispersion of equipment following a derailment. This is important because one of the key
datasets used in this analysis is the NTSB data. This data was generated during the late 1970’s and early 1980’s. While there have been substantial safety and productivity improvements on the North American railways and significant metallurgical improvements to rail components, the basic design of North American track and freight rolling stock has been maintained. Consequently, it is assumed that irrespective of the materials, once a train has left the tracks, physics takes over.

In the analysis of costs, it is assumed that no additional right-of-way costs will be incurred, as these would be covered under the procurement and construction of the railway. This analysis looks at the marginal cost of implementing mitigations to a railway that is already designed. It is assumed that any appropriate track separation distance will be determined by the stakeholders involved in designing and developing a railway. The authors are presenting a process to estimate, understand, and manage the risk impacts of a particular target track separation value.

THE DISPERSION EXCEEDANCE PROBABILITY DENSITY FUNCTION

The Dispersion Exceedance Probability Density Function (PDF) is key to this entire analysis because it identifies the travel distance probability of equipment from a freight train derailment. In 2007, Transys Research Ltd., published the report “Evaluation of Risk Associated with Stationary Dangerous Goods Railway Cars” English, et. al. [1] which utilized data from approximately 1,300 derailment incidences on North American freight railroads. The authors recreated this from the NTSB data set, and confirmed the form of the dispersion PDF presented in that report, and that it also follows a gamma distribution as shown below. This is important because a gamma distribution is appropriate for the statistical analysis of a sample set of non-zero values.

\[
P(D) = \frac{1}{\beta^\alpha \Gamma(\alpha)} \cdot D^{\alpha-1} \cdot e^{-\frac{D}{\beta}}
\]

where,

- \( P(D) \): the probability at which the maximum dispersion is \( D \)
- \( D \): Maximum dispersion (displayed in feet)
- \( \Gamma \): the gamma function (where, \( \Gamma(\alpha) = \int_0^{\infty} t^{\alpha-1} e^{-t} dt \))
- \( \alpha \): the shape parameter
- \( \beta \): the scale parameter

The NTSB data is from accidents recorded in the decades of 1970 and 1980. Since then, and particularly following the Staggers Act in 1982, there have been dramatic improvements in railway infrastructure and equipment management and performance monitoring technology that have vastly improved safety on the railways. However, the laws of physics still prevail, and the data is still considered to be relevant in the context of equipment behavior once a train has left the rails.

Figure 1 presents the actual NTSB data and five separate gamma distributions based on different shape (\( \alpha \)) and scale (\( \beta \)) parameters. All of the shape and scale parameters provide good results, and the values of \( \alpha = 1.2 \), and \( \beta = 33.0 \) were selected as providing a reasonable fit. This established the form of the function that is applied to the probability of a derailment to estimate the probability that equipment may disperse to a specific distance away from the track centerline following a derailment. In turn, this is used to inform the probability of a derailment fouling another track located a known distance from the track on which the derailment occurred.

A range of 0 to 300 ft of distance is considered in this analysis, with 300 ft being the upper bound. It is worth noting that at a track separation distance of 300 ft, the estimated fouling probability per million train miles is 0.00230, or the equivalent to one fouling incident per approximately 435 million train miles. Putting this into perspective, a 200-mile long freight track carrying 30 million gross tons per year at an average train weight of 6,000 tons will incur approximately one million train miles per year. So, at 300 ft track separation, the probability of a fouling incident on the other rail tracks would be about once every 435 years.
An analysis of incident rates by FRA Track Class and FRA Cause Code was used to estimate derailment probability [4]. Because this analysis was focused on analyzing derailments with respect to train-miles, the team reached out to BNSF Railway Company, who agreed to provide traffic density and reportable derailment data for this analysis.

Table 1 presents the output of the derailment analysis calculations of derailments per train-mile for FRA Track Class 3, based on average annual train-miles of BNSF traffic, the miles of Track Class 3 in the BNSF system, and the average number of derailments per year on that track class.

Using the dispersion PDF presented in Figure 1, and the per-train-mile derailment rate from the BNSF reportable derailment and track density data, we can generate an estimated probability of dispersion per train mile \((F(D))\) traveled as follows:

\[
F(D) = 11.81 P(D)
\]

where \(\alpha = 1.2\), and \(\beta = 33.0\).

Figure 2 presents the profile of aforementioned \(F(D)\), the estimated number of fouling incidents per million train miles from freight track in which equipment is dispersed a specific distance from the freight track centerline.
RISK MITIGATION PROCESS

There is assumed to be a “target” track separation distance at which no mitigation would be necessary because the attendant risk would be considered as reasonable and acceptable. Furthermore, at track separation distances less than that target value, mitigations can be systematically applied to achieve a risk value equal to or less than the target track separation distance. Analysis of costs and combinations of mitigations can then identify an optimized solution to achieve the target risk threshold.

Figure 2: Estimated Fouling by Track Separation Distance

The analysis process is as follows:

- **Step 1:** Assume a target separation value for which no mitigation would be required. For example, the authors have used a track separation distance of 100 ft. The authors note that the attendant risk is not zero for a track separation distance of 100 ft, but are assuming for the purposes of this analysis that such a separation distance provides a reasonable and acceptable risk threshold.

- **Step 2:** Determine the Track Fouling Probability per one million train miles. For a track separation distance of 100 ft, the estimated track fouling probability is 0.818. This means that for every one million train miles, there is an estimated 0.818 instances in which a derailment would foul a track 100 ft away from the track on which the derailment occurred.

- **Step 3:** For all track with a separation distance of less than 100 ft, incrementally implement mitigation techniques that will reduce the probability of fouling to at least the probability equal to a track separation distance of 100 ft.

- **Step 4:** Analyze combinations of mitigation solutions to determine the least cost set of solutions to achieve the target threshold.

The first three steps to this approach are shown in Figure 3.
RISK MITIGATION MEASURES

The risk mitigation measures considered in this analysis include derailment prevention and derailment barrier techniques, and are not exhaustive of all options available. Derailment prevention techniques considered are Vehicle Inspection Monitoring technologies, and improving the FRA Track Class. Barrier techniques include either an earth berm or a concrete wall, the first choice being an earth berm because of cost, followed by a concrete wall. Earth berms are limited to track separations of 40 ft or greater due to berm slope and construction constraints. Concrete walls are used for separation distances less than 40 ft. In the analysis presented here, there is a sensitivity case in which concrete walls are the only mitigation considered, and are therefore used wherever mitigation is required irrespective of the separation distance.

Each of these mitigations has an effectiveness value, an initial capital cost, and on-going maintenance costs. The derailment prevention mitigations are presented in Table 2, and barrier mitigations are presented in Table 5.

<table>
<thead>
<tr>
<th>Mitigation Measure</th>
<th>% Derailment Reduction</th>
<th>Capital Cost</th>
<th>Annual O&amp;M Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Inspection Technology Package (per corridor)</td>
<td>20.5%</td>
<td>$4,280,000</td>
<td>$1,020,000</td>
</tr>
<tr>
<td>FRA Track Class Improvement (per mile)</td>
<td>6.4%</td>
<td>$1,500,000</td>
<td>$225,000</td>
</tr>
</tbody>
</table>
The derailment percent reduction values in Table 2 are based upon the estimated reduction in mechanical- and track-related incidents, and the percentage of those incident types reported to the FRA. For example, over a 5-year period, BNSF recorded 653 reportable incidents, of which 208 (31.85%) and 251 (38.44%) were mechanical related or track related, respectively.

BNSF Railway Company is a leader in implementing new vehicle monitoring technologies that identify poorly performing “bad actor” equipment so that these vehicles can be removed from service at an appropriate time. BNSF has determined that the best way to implement these monitoring technologies is as a package of complementing technologies. Table 3 presents the package of monitoring technologies considered in this analysis. In the context of this analysis, the entire package of monitoring technology is installed at each end of the corridor, and in some cases along the way, so that all traffic entering and leaving the corridor is monitored.

Historical data indicates that through implementation of such monitoring technology, mechanical derailments have decreased by approximately 64.2%. Derailment statistics between FRA Track Class 3 and Track Class 5 indicate a derailment reduction of approximately 16.6% for the higher track class.

Based on BNSF’s incident reduction experience, the estimated overall derailment reductions as a result of the implementing these two mitigations in an area where no such improvements currently exist can be expected to yield total incident reductions of 20.5% and 6.4%, respectively.

Table 3: Derailment Prevention Technologies – Estimated Costs and Corridor Quantities

<table>
<thead>
<tr>
<th>Derailment Prevention Technology</th>
<th>Name</th>
<th>Unit Capital Cost</th>
<th>Unit O&amp;M Cost</th>
<th>Qty</th>
<th>Total Capital Cost</th>
<th>Total O&amp;M Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Bearing Detector</td>
<td>ABD</td>
<td>$250,000</td>
<td>$56,000</td>
<td>2</td>
<td>$500,000</td>
<td>$112,000</td>
</tr>
<tr>
<td>Wheel Impact Load Detector</td>
<td>WILD</td>
<td>$250,000</td>
<td>$30,000</td>
<td>2</td>
<td>$500,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>Truck Performance Detector</td>
<td>TPD</td>
<td>$200,000</td>
<td>$30,000</td>
<td>2</td>
<td>$400,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>Axle Alignment Detector</td>
<td>OGD</td>
<td>$650,000</td>
<td>$186,000</td>
<td>2</td>
<td>$1,300,000</td>
<td>$372,000</td>
</tr>
<tr>
<td>Hot Bearing Detector</td>
<td>HBD</td>
<td>$25,000</td>
<td>$8,000</td>
<td>8</td>
<td>$200,000</td>
<td>$64,000</td>
</tr>
<tr>
<td>Hot/Cold Wheel Detector</td>
<td>HWD</td>
<td>$30,000</td>
<td>$8,000</td>
<td>8</td>
<td>$240,000</td>
<td>$64,000</td>
</tr>
<tr>
<td>Truck Hunting Detector</td>
<td>THD</td>
<td>$150,000</td>
<td>$30,000</td>
<td>2</td>
<td>$300,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>Machine Vision System</td>
<td>MVS</td>
<td>$220,000</td>
<td>$84,000</td>
<td>2</td>
<td>$440,000</td>
<td>$168,000</td>
</tr>
<tr>
<td>Cracked Wheel Acoustic Detector</td>
<td>CWAD</td>
<td>$200,000</td>
<td>$30,000</td>
<td>2</td>
<td>$400,000</td>
<td>$60,000</td>
</tr>
<tr>
<td><strong>Total Investment and On-Going Maintenance</strong></td>
<td><strong>$4,280,000</strong></td>
<td><strong>$1,020,000</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
Table 4: Derailment Reduction Calculations

<table>
<thead>
<tr>
<th>Incident Cause (FRA)</th>
<th>Qty</th>
<th>% of Total</th>
<th>Incident Reduction</th>
<th>Estimated Overall Derailment Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Related</td>
<td>208</td>
<td>31.9%</td>
<td>64.2%</td>
<td>20.5%</td>
</tr>
<tr>
<td>Track Related</td>
<td>251</td>
<td>38.4%</td>
<td>16.6%</td>
<td>6.4%</td>
</tr>
<tr>
<td>Total of All Incidents (5-yrs)</td>
<td>653</td>
<td>100%</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Barrier mitigations are presented in Table 5, along with assumed effectiveness and costs.

Table 5: Barrier Mitigation Measure Cost and Effectiveness

<table>
<thead>
<tr>
<th>Mitigation Measure</th>
<th>% Barrier Effectiveness</th>
<th>Capital Cost</th>
<th>Annual O&amp;M Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Earth Berm* (per mile)</td>
<td>80.0%***</td>
<td>$680,000</td>
<td>$68,000</td>
</tr>
<tr>
<td>Concrete Wall** (per mile)</td>
<td>95.0%***</td>
<td>$13,600,000</td>
<td>$136,000</td>
</tr>
</tbody>
</table>

* estimate based on 12 ft high earth berm with 1.3:1 slope
** estimate based on 12 ft. high x 3.3 ft thick concrete wall
*** assumption by authors

RISK MITIGATION ANALYSIS

A model was developed to consider a corridor in which both freight and high speed rail tracks operate. The corridor selected was one of the alternatives studied, and due to proprietary reasons is not discussed in detail within this paper. In the corridor, the freight and high speed rail tracks have track separation distances as close as 15 feet and up to several miles apart. The notional image of the segmentation of the tracks associated with the separation distance between freight and HSR alignment is shown in Figure 4, where Di denotes the separation in the segment i.

Figure 4: Image of Segmentation and Separation Distance

The model looks at each segment individually, and applies mitigations as needed, in the following order, and based on actual versus target track separation distance.

1. Vehicle Inspection Technology
2. Track Class Improvement  
3. Earth Berm  
4. Concrete Wall

The modeling process flow chart is presented in Figure 5. Here the risk mitigation implementation plan is derived in the final process thorough segment level analysis, the detail of which is presented in Figure 6. The model applies each mitigation in order, if needed, and calculates the adjusted risk value from that mitigation. This process continues until the risk value for the actual track segment is satisfied with respect to the target value. It then moves to the next segment until the entire corridor is analyzed.

![Figure 5: Modeling Process Flow Chart](image)

![Figure 6: Segment Level Analysis](image)
In this analysis, a target track separation distance of 100 feet is used. This means that for any track where track separations are 100 feet or greater, no mitigations will be required.

Table 6 shows how the modeling process works for a track segment with track separation distances of 40 ft and 90 ft. The process illustrated in Table 6 is repeated for each track segment in the corridor until the risk threshold for all segments is satisfied.

- The target risk value at a 100 ft track separation is 0.818, while the risk values at 40 ft and 90 ft separation are 4.433 and 1.090, respectively. By implementing Vehicle Inspection technology, the 40-ft and 90-ft risk values are reduced to 3.526 and 0.867. In terms of a “virtual” track separation distance, the risks are approximately that of 45-ft and 95-ft track separation distances.
- Next, the Track Class is improved from Track Class 3 to Track Class 5. In the 40-ft case, this reduces the risk value to 3.301, or similar to 50-ft track separation; however, in the 90-ft case, this reduces the risk value to 0.811, which satisfies the risk threshold at 100 ft (<0.818). This implies that no further mitigation will be required for the latter case.
- Because the risk value is still too high for the 40-ft case, an Earth Berm is constructed between the tracks which reduces the value down to 0.660, which is “virtual” track separation distance of 105 ft, and thereby satisfying the risk threshold.

### Table 6: Mitigation Analysis Steps (top: 40ft, bottom: 90ft)

<table>
<thead>
<tr>
<th>Mitigation</th>
<th>Estimated Risk Reduction</th>
<th>Target Value</th>
<th>Actual Spacing</th>
<th>Virtual Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
<td>Risk Value</td>
<td>ft</td>
<td>Risk Value</td>
</tr>
<tr>
<td>No Mitigation</td>
<td>0%</td>
<td>100</td>
<td>0.818</td>
<td>40</td>
</tr>
<tr>
<td>add Vehicle Inspection</td>
<td>20.5%</td>
<td>100</td>
<td>0.818</td>
<td>40</td>
</tr>
<tr>
<td>add Track Class Improvement</td>
<td>6.4%</td>
<td>100</td>
<td>0.818</td>
<td>40</td>
</tr>
<tr>
<td>add Earth Berm</td>
<td>80%</td>
<td>100</td>
<td>0.818</td>
<td>40</td>
</tr>
</tbody>
</table>

### Table 6: Mitigation Analysis Steps (top: 40ft, bottom: 90ft)

<table>
<thead>
<tr>
<th>Mitigation</th>
<th>Estimated Risk Reduction</th>
<th>Target Value</th>
<th>Actual Spacing</th>
<th>Virtual Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>ft</td>
<td>Risk Value</td>
<td>ft</td>
<td>Risk Value</td>
</tr>
<tr>
<td>No Mitigation</td>
<td>0%</td>
<td>100</td>
<td>0.818</td>
<td>90</td>
</tr>
<tr>
<td>add Vehicle Inspection</td>
<td>20.5%</td>
<td>100</td>
<td>0.818</td>
<td>90</td>
</tr>
<tr>
<td>add Track Class Improvement</td>
<td>6.4%</td>
<td>100</td>
<td>0.818</td>
<td>90</td>
</tr>
<tr>
<td>add Earth Berm</td>
<td>80%</td>
<td>100</td>
<td>0.818</td>
<td>Not required</td>
</tr>
</tbody>
</table>

### ANALYSIS RESULTS

Five cases were analyzed, using different combinations of mitigations.
- Case 1: Vehicle Inspection, Track Class Improvement, Earth Berm, Concrete Wall
- Case 2: Track Class Improvement, Earth Berm, Concrete Wall
- Case 3: Vehicle Inspection, Earth Berm, Concrete Wall
- Case 4: Earth Berm, Concrete Wall
- Case 5: Concrete Wall

The results of the analysis are presented in Table 7. The 30-Year NPV is based on a 3.5% discount rate. It is interesting to look at how the mitigations are applied over the corridor, as this
significantly affects the overall economics. The implementation percent for the various mitigations for each of the cases is presented in Table 8.

### Table 7: Analysis Results (30-Yr NPV @ 3.5% Discount Rate)

<table>
<thead>
<tr>
<th>Mitigation Package</th>
<th>30-Yr NPV (millions)</th>
<th>Cost Efficiency $ per mile</th>
<th>Virtual Track Separation (ft) (segment weighted average for entire corridor)</th>
<th>Incident Interval Risk (years, per Million Train Miles)**</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pre-Mitigation*</td>
<td>Post-Mitigation*</td>
</tr>
<tr>
<td><strong>Case 1:</strong></td>
<td></td>
<td></td>
<td>85</td>
<td>150</td>
</tr>
<tr>
<td>- Vehicle Inspection</td>
<td>$1,485</td>
<td>$6,481,898</td>
<td>85</td>
<td>150</td>
</tr>
<tr>
<td>- Track Class</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Earth Berm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Concrete Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Case 2:</strong></td>
<td></td>
<td></td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Track Class</td>
<td>$1,468</td>
<td>$6,409,790</td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Earth Berm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Concrete Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Case 3:</strong></td>
<td></td>
<td></td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Vehicle Inspection</td>
<td>$198</td>
<td>$865,764</td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Earth Berm</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Concrete Wall</td>
<td></td>
<td></td>
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<td></td>
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<tr>
<td><strong>Case 4:</strong></td>
<td></td>
<td></td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Earth Berm</td>
<td>$219</td>
<td>$954,093</td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Concrete Wall</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Case 5:</strong></td>
<td></td>
<td></td>
<td>85</td>
<td>180</td>
</tr>
<tr>
<td>- Concrete Wall</td>
<td>$1,434</td>
<td>$6,260,329</td>
<td>85</td>
<td>180</td>
</tr>
</tbody>
</table>

* Virtual Track Separation distance is the approximate distance value associated with the weighted average of the original risk values (for Pre-Mitigation) and achieved calculated risk values (for Post-Mitigation) for the entire corridor, defined as follows:

\[
\text{Virtual Track Separation distance} = F^{-1}\left(\frac{\sum_{i=1}^{N} L_i \cdot R_i}{\sum_{i=1}^{N} L_i}\right)
\]

where, \(N\) is the total number of segments for entire corridor, \(L_i\) is the length of segment \(i\), \(R_i\) is the risk value of segment \(i\), and \(F^{-1}(R)\) is the inverse function of \(R=F(D)\).

** Incident Interval is based on the weighted average of the achieved calculated risk values for the entire corridor, that is:

\[
\text{Incident Interval} = 1/F \text{ (Virtual Track Separation at Post Mitigation)}
\]

It is assumed that the Track Class Improvement will be applied to the entire corridor, as maintaining multiple individual segments to different FRA track classes would be unattractive from a maintenance management perspective.

Likewise, since Vehicle Inspection technology is applied to all the traffic entering and leaving the corridor, it is effectively applied to the entire corridor in all cases where Vehicle Inspection technology is considered.

Earth Berm and Concrete Wall mitigations are applied only when and where needed.

An interesting feature of the results is that when Case 2 and Case 3 are compared, the implementation proportion of the required application of Earth Berm did not show significant difference (both rounded to 38.2%), although the different mitigation technology (Track Class Improvement/Vehicle Inspection) had been applied before Earth Berm was applied during the analysis. This was surprising because the effectiveness of Vehicle Inspection (20.46%) is much greater than that of Track Class Improvement (6.37%). The reason for this is that the track separation that makes a difference in
determining whether another mitigation method needs to be accompanied is only limited to 95 ft and its small vicinities and there are few instances of the 95 ft separation in the alignment. This highlights the sensitivity to assumed effectiveness values and track alignment characteristics. A different alignment or slight changes to effectiveness could significantly change the outcome. Table 9 compares the contribution of above two mitigation methods to risk reduction with respect to track separation.

<table>
<thead>
<tr>
<th>Track Separation (ft)</th>
<th>Risk Value</th>
<th>With Track Improvement</th>
<th>With Vehicle Inspection Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>85</td>
<td>1.26</td>
<td>1.18</td>
<td>1.00</td>
</tr>
<tr>
<td>90</td>
<td>1.09</td>
<td>1.02</td>
<td>0.867</td>
</tr>
<tr>
<td>95</td>
<td>0.944</td>
<td>0.884</td>
<td>0.751 (&lt;0.818)</td>
</tr>
<tr>
<td>98</td>
<td>0.866</td>
<td>0.811 (&lt;0.818)</td>
<td>0.689 (&lt;0.818)</td>
</tr>
<tr>
<td>100</td>
<td>0.818</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>

CONCLUSIONS

In this paper a robust analytical approach was presented, by which dispersion risk from freight derailments in shared right-of-way corridors is quantified. The risk varies with the distance between the freight and high-speed tracks, and that risk can be managed by the application of mitigation measures to achieve a reasonable and acceptable threshold. The implementation plan that is derived serves as a useful and powerful tool for identification of cost effective combinations of mitigation measures as well as a reasonable life-cycle indicator.
In this analysis, the target track separation value of 100 ft was selected, in part because it is a value that is easily related to, but also, the length of most rolling stock falls within this dimension. There is no set standard for the target or for the target used in this analysis.

The results of the analysis showed that the 100-ft target could be satisfied by all mitigation cases. However, the cost to implement the technologies varied greatly.

There is wide variance in the cost of solutions. Case 3 and Case 4 are the least costly, with NPVs of $198 million and $219 million, respectively, and both achieve the same level of risk protection of 145 ft virtual track separation. The additional implementation cost of Vehicle Inspection technology in Case 3 indicated a life-cycle cost savings of around $20 million due to a reduction in barrier technology construction.

Case 1 is the most expensive package of mitigations, with an NPV of $1.485 billion; and, with a virtual track separation distance of 150 ft, achieves a risk threshold similar to Case 3 and Case 4.

Case 5 is the third most costly option, with an NPV of $1.434 billion; but, it also provides the highest level of risk mitigation with a virtual track separation distance of 180 ft.

The analysis methodology is robust as presented here, however, it should be considered as only indicative of a generalized set of corridor and traffic characteristics. Before applying this analysis method to a specific corridor, the individual assumptions regarding alignment and traffic characteristics should be also considered. For example, on a specific route, there may be locations which are historically prone to derailments, such as around special track work. Future work is being considered to better understand the impact of derailment locations to potentially further optimize mitigations.

Reference[s]

2. Barkan, C.P.L, “Distance From Track Center of Railroad Equipment in Accidents”, University of Illinois at Urbana-Champaign, 1989.
ANALYTICAL METHOD TO CALCULATE RISK-BASED TRACK SEPARATION DISTANCES FOR HIGH SPEED TRACKS IN FREIGHT CORRIDORS

Steven L. Clark, PE (Arup USA)
Shaun McCabe (Texas Central High Speed Railway, LLC)
Junichiro Kubo, PhD (Central Japan Railway Company)
DJ Mitchell (BNSF Railway Company)
Today’s Presentation

• Purpose and Approach
• Modeling Results
• Future Model Developments
• Questions and Answers

Purpose and Approach

• Purpose:
  • Risk Management
    • Fouling of HSR tracks in proximity to Freight tracks
    • Optimized solution
  • Approach
    • Conduct analysis of NTSB, FRA, and BNSF network-wide data
    • Robust probabilistic analysis
    • Assess implementation of mitigation measures
    • Identify best approach to manage risk
      • Life-cycle Cost
      • Appropriate level of safety

Derailment Dispersion

From English et.al.

Figure 10 NTSB database derailment dispersion versus speed

Track Separation on the Alignment

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Philosophical Approach

- There is assumed to be a “target” track separation distance at which no mitigation would be necessary because the attendant risk would be considered as reasonable and acceptable.
- At track separation distances less than that target value, mitigations can be systematically applied to achieve a risk value equal to or less than the target track separation distance.
- Analysis of costs and combinations of mitigations can then identify an optimized solution to achieve the target risk threshold.

FRA Data Analysis - 1

FRA Data Analysis - 2

FRA Data Analysis - 3

FRA Data Analysis - 4

Model Approach

- Segment-by-Segment Analysis
  - Separation Distance
- Apply mitigation measures incrementally to achieve the target “virtual” separation distance (i.e., 100 ft)
  - Once satisfied, moves to next segment
  - Continues until all alignment segments re analyzed
Track Separation on the Alignment

Segment j
(Dj = \text{**})

Segment j+1
(Dj+1 = \text{**})

Segment j+2
(Dj+2 = \text{**})

Segment k
(Dk > 300)

Freight

HSR

Process Flow Chart - Overall Process

Dispersion Exceedance Probability Function (DEP)

Dispersion Exceedance Probability Function (DEP)

NTSB Data

Dispersion Exceedance Probability Function

Gamma(1.46, 28.68)

Lateral Displacement (ft)

Exceedance Probability

Derailment Rates

<table>
<thead>
<tr>
<th>Class of Track</th>
<th>Annual Train mi</th>
<th>Miles of Track by Class</th>
<th>Derailments per Year</th>
<th>Train Miles per Year</th>
<th>Derailments per Train Mi per Year</th>
</tr>
</thead>
<tbody>
<tr>
<td>Class 2</td>
<td>308,590</td>
<td>1,975</td>
<td>24.5</td>
<td>565,175</td>
<td>4.339E-05</td>
</tr>
<tr>
<td>Class 3</td>
<td>638,482</td>
<td>1,662</td>
<td>21.4</td>
<td>1,811,321</td>
<td>1.181E-05</td>
</tr>
<tr>
<td>Class 4</td>
<td>6,316,768</td>
<td>13,282</td>
<td>45.6</td>
<td>29,548,214</td>
<td>1.542E-06</td>
</tr>
<tr>
<td>Class 5</td>
<td>3,698,273</td>
<td>5,035</td>
<td>5.9</td>
<td>14,600,556</td>
<td>4.033E-07</td>
</tr>
<tr>
<td>Totals</td>
<td>21,954</td>
<td>97.4</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Notes
1. Average over 4 years, 2009-2012, BNSF Data
2. Average over 5.75 years (2007-3Q2012), FRA Data

Estimated Rate of Fouling

Estimated Fouling Rate by Track Separation Distance

(FRA Track Class 3, per million train-miles)
**Target Track Separation Distance Risk**

Estimated Fouling Rate by Track Separation Distance (FRA Track Class 3, per million train-miles)

- **Step 1**
  - \(d = 100 \text{ ft} \)

- **Step 2**
  - \(p = 0.8184 \)

- **Step 3**
  - Apply mitigations to separation distances less than 100 ft to achieve fouling rate value of 0.8184

**Mitigation Process to achieve Target Risk**

**Mitigation Examples**

<table>
<thead>
<tr>
<th>Mitigation</th>
<th>Estimated Risk Reduction</th>
<th>Target Value</th>
<th>Actual Spacing</th>
<th>Virtual Spacing</th>
</tr>
</thead>
<tbody>
<tr>
<td>No Mitigation</td>
<td>0%</td>
<td>100 ft</td>
<td>0.818 ft</td>
<td>40 ft</td>
</tr>
<tr>
<td>add Vehicle Inspection</td>
<td>20.5%</td>
<td>100 ft</td>
<td>0.818 ft</td>
<td>3.924 ft</td>
</tr>
<tr>
<td>add Track Class Improvement</td>
<td>6.4%</td>
<td>100 ft</td>
<td>0.818 ft</td>
<td>3.301 ft</td>
</tr>
<tr>
<td>add Earth Berm</td>
<td>80%</td>
<td>100 ft</td>
<td>0.818 ft</td>
<td>0.660 ft</td>
</tr>
</tbody>
</table>

- **40-ft Actual Spacing**

- **90-ft Actual Spacing**

**Model Approach**

- **Five Cases**
  1. Vehicle Inspection, Track Class Improvement, Earth Berm, Concrete Wall
  2. Track Class Improvements, Earth Berm, Concrete Wall
  3. Vehicle Inspection, Earth Berm, Concrete Wall
  4. Earth Berm, Concrete Wall
  5. Concrete Wall

**Data Received from BNSF (1)**

- **Mechanical Derailment Trends**
  - Impacts from implementing wayside vehicle inspection technologies
  - Improvements result from total package implementation
  - 8% YOY decline in Mechanical Derailments (2000 to 2012)
Data Received from BNSF (2)

- **Track-related Derailment Trends**
  - Analysis of subdivision performance
  - Informs performance improvement between FRA track Classes
  - Impacts influenced by components and geometry
  - Requires detailed assessment of specific asset conditions
  - 16.6% decrease between Track Class 3 and Track Class 5

### Mechanical and Track Related Incidents

<table>
<thead>
<tr>
<th>Incident Cause (FRA)</th>
<th>Qty</th>
<th>% of Total</th>
<th>Incident Reduction</th>
<th>Estimated Overall Derailment Reduction</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mechanical Related</td>
<td>208</td>
<td>31.9%</td>
<td>64.2%</td>
<td>20.5%</td>
</tr>
<tr>
<td>Track Related</td>
<td>251</td>
<td>38.4%</td>
<td>16.6%</td>
<td>4.4%</td>
</tr>
<tr>
<td>Total of All Incidents</td>
<td>653</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Mitigation Technologies

- **Input Cost Assumptions**
  - 30-yr NPV at 3.5% Discount Rate
  - Capital and Annual O&M

<table>
<thead>
<tr>
<th>Mitigation Measure</th>
<th>% Derailment Reduction</th>
<th>Capital Cost</th>
<th>Annual O&amp;M Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle Inspection Technology</td>
<td>20.5%</td>
<td>$4,280,000</td>
<td>$1,020,000</td>
</tr>
<tr>
<td>Track Class Improvement (per mile)</td>
<td>6.4%</td>
<td>$1,500,000</td>
<td>$225,000</td>
</tr>
<tr>
<td>Earth Berm (per mile)</td>
<td>80%</td>
<td>$680,000</td>
<td>$68,000</td>
</tr>
<tr>
<td>Concrete Wall (per mile)</td>
<td>95%</td>
<td>$13,600,000</td>
<td>$136,000</td>
</tr>
</tbody>
</table>

Vehicle Inspection Technology Package

<table>
<thead>
<tr>
<th>Derailment Prevention Technology</th>
<th>Name</th>
<th>Unit Capital Cost</th>
<th>Unit O&amp;M Cost</th>
<th>Qty</th>
<th>Total Capital Cost</th>
<th>Total O&amp;M Cost</th>
</tr>
</thead>
<tbody>
<tr>
<td>Acoustic Bearing Detector</td>
<td>ABD</td>
<td>$250,000</td>
<td>$56,000</td>
<td>2</td>
<td>$500,000</td>
<td>$112,000</td>
</tr>
<tr>
<td>Wheel Impact Load Detector</td>
<td>WILD</td>
<td>$250,000</td>
<td>$30,000</td>
<td>2</td>
<td>$500,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>Truck Performance Detector (force based)</td>
<td>TPD</td>
<td>$200,000</td>
<td>$30,000</td>
<td>2</td>
<td>$400,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>Axle Alignment Detector (laser based)</td>
<td>OGD</td>
<td>$650,000</td>
<td>$186,000</td>
<td>2</td>
<td>$1,300,000</td>
<td>$372,000</td>
</tr>
<tr>
<td>Hot Bearing Detector</td>
<td>HBD</td>
<td>$25,000</td>
<td>$8,000</td>
<td>8</td>
<td>$200,000</td>
<td>$64,000</td>
</tr>
<tr>
<td>Hot/Cold Wheel Detector</td>
<td>HWD</td>
<td>$30,000</td>
<td>$8,000</td>
<td>8</td>
<td>$240,000</td>
<td>$64,000</td>
</tr>
<tr>
<td>Truck Hunting Detector</td>
<td>THD</td>
<td>$150,000</td>
<td>$30,000</td>
<td>2</td>
<td>$300,000</td>
<td>$60,000</td>
</tr>
<tr>
<td>Machine Vision System</td>
<td>MVS</td>
<td>$220,000</td>
<td>$84,000</td>
<td>2</td>
<td>$440,000</td>
<td>$168,000</td>
</tr>
<tr>
<td>Cracked Wheel Acoustic Detector</td>
<td>CWAD</td>
<td>$200,000</td>
<td>$30,000</td>
<td>2</td>
<td>$400,000</td>
<td>$60,000</td>
</tr>
</tbody>
</table>

Total Investment and On-Going Maintenance:

- $4,280,000
- $1,020,000

Mitigations and Order of Application (1)

- **Vehicle Inspection Package**
  - Applied to entire corridor even if needed by only one segment
  - Assumes installation at each end of corridor
  - Some instrumentation along the ROW (HBD, HWD)

- **Track Class Improvement**
  - Applied to entire corridor even if needed by only one segment

Mitigations and Order of Application (2)

- **Earth Berm**
  - Where needed, and track separation > 40 feet
  - **Case 4: >45 feet**

- **Concrete Wall**
  - Where needed, and track separation < 40 feet
  - Excludes Concrete Wall Only case (applied where needed)
Results: 100-ft Separation Threshold

<table>
<thead>
<tr>
<th>Mitigation Package</th>
<th>30-Yr NPV (millions)</th>
<th>Cost Efficiency $ per mile (millions)</th>
<th>Virtual Track Separation (ft) (corridor weighted average)</th>
<th>Incident Interval Risk (years, per Million Train Miles)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Pre-Mitigation</td>
<td>Post-Mitigation</td>
<td></td>
<td></td>
</tr>
<tr>
<td>- Vehicle Inspection</td>
<td>$1,485</td>
<td>$6.5</td>
<td>85</td>
<td>150</td>
</tr>
<tr>
<td>- Track Class</td>
<td>$1,468</td>
<td>$6.4</td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Earth Berm</td>
<td>$198</td>
<td>$0.9</td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Concrete Wall</td>
<td>$219</td>
<td>$1.0</td>
<td>85</td>
<td>145</td>
</tr>
<tr>
<td>- Concrete Wall</td>
<td>$1,434</td>
<td>$6.3</td>
<td>85</td>
<td>180</td>
</tr>
</tbody>
</table>

Conclusions

Conclusions (1)

- We established a robust analytical approach
  - Quantifies dispersion from freight derailments in proximity to other tracks

- All Cases achieve a 100-ft Threshold

- 100-ft separation is not a suggested threshold
  - Used only to demonstrate the process
  - To be determined by owner/operator stakeholders

Conclusions (2)

- Wide Range in Cost and Effectiveness
  - Based on Weighted Average Fouling Rate
  - Least Cost: Case 3 ($198 million)
  - Highest Cost: Case 1 ($1.5 billion)
  - Most Effective: Case 5 (20.5 years per million TM)
  - Least Effective: Case 3 (7.6 years per million TM)

Future Model Developments

Future Model Developments

- Model Refinements
  - Mitigation Costs
  - Risk Management Threshold
  - High Probability Locations
  - Curves, Turnouts, Other?
- Incorporate into Design and Development Process
  - Apply to a real alignment
  - Optimize track separations
  - Incorporate vertical separations
  - Incorporate actual traffic (million train miles)
- Incorporate Cost into Financial Model
Thank You!