Optimization of Rail Defect Inspection Frequency to Reduce Railroad Hazardous Materials Transportation Risk

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ABSTRACT

Railroads safely and efficiently transport hazardous materials. While the society derives significant benefits from rail transport of hazardous materials, the associated accident risks must be appropriately managed. There is growing interest from the government, railroad industry and public to optimize all approaches to effectively reduce hazardous materials transportation risk. A hazardous materials release incident can be due to various accident causes, among which broken rails are the most frequent causes. Ultrasonic rail defect inspection is commonly used to prevent broken-rail-caused train accidents, thereby reducing hazardous materials transportation risk. However, little prior research has been conducted to quantify the relationship between hazardous materials release risk and rail defect inspection frequency, nor how to optimize rail inspection schedules to maximize risk reduction across a range of resource availability. In this paper, a decision support tool is developed to determine the optimal rail defect inspection frequency of different track segments in order to reduce route risk in the most cost-efficient manner. The methodology and results are intended to assist decision makers for local, regional and system-wide risk management of hazardous materials transportation by rail.

Keywords: Hazardous Materials Transportation, Train Derailment, Rail Defect Inspection, Risk Reduction

1   INTRODUCTION

Hazardous materials (hazmat) transportation is important for the American economy and a major source of revenue for railroads. Although the vast majority of railroad hazmat shipments reach their destinations without a release incident, they still represent a safety concern for both the public and private sections due to the potential great impact of a hazmat release incident. There is continual interest in minimizing the risk associated with hazmat transportation in the most cost-efficient manner. There are two basic strategies to reduce hazmat release risk: (1) reduce the likelihood of a hazmat release incident; (2) reduce release consequences. This study focuses on the former – reducing the likelihood of a hazmat release incident by preventing major accident causes.

In terms of preventing accident causes to reduce the likelihood of a hazmat release incident, it is first necessary to identify the distribution of number of hazmat cars derailed by accident cause. The data used in this study are from the Federal Railroad Administration (FRA) Rail Equipment Accident (REA) database. The FRA REA database contains information regarding all accidents that exceed a monetary threshold of damages to on-track equipment, signals, track, track structures, and roadbed (*1*). Using this database, the analysis shows that broken-rail-related accident causes resulted in 26% (106 out of 412) hazmat cars releasing due to train derailments on U.S. railroads from 2002 to 2011 (Figure 1). Therefore, broken rail prevention is identified as one promising risk reduction strategy (*2-5*).
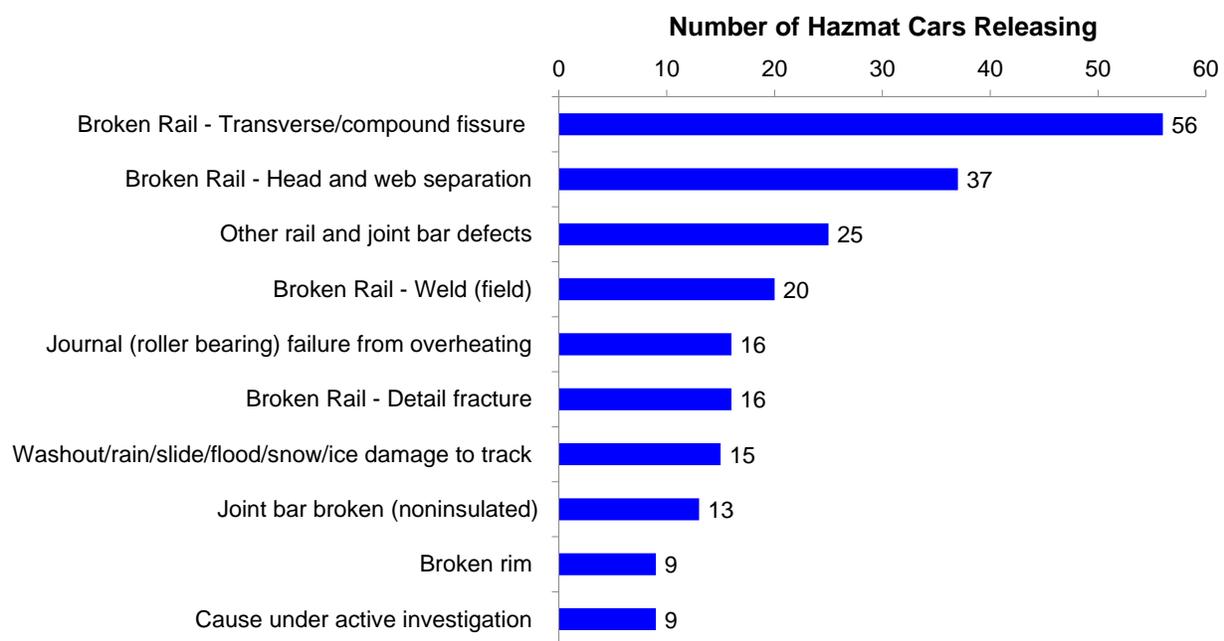
Number of Hazmat Cars Releasing

Figure 1 Top 10 causes of number of hazmat cars releasing in freight-train derailments on U.S. railroads from 2002 to 2011

There are various approaches to prevent broken rails, including rail grinding (*6*), lubrication (*7*), rail replacement and renewal (*8*), and non-destructive rail defect inspection (*9-11*). This paper focuses on ultrasonic rail defect inspection, the primary non-destructive inspection technology used by American railroads since the 1930s (*12*). The principal purpose of

rail defect inspection is to identify rail defects before they grow to critical fracture size and cause broken rail derailments that may result in events such as a hazardous materials release. However, little is known regarding the relationship between hazardous materials release risk and rail inspection frequency, nor how to optimize and prioritize rail inspection schedules to reduce the risk in the most cost-efficient manner. Addressing these questions is crucial for railroads to prioritize their infrastructure maintenance activities and implement the optimal portfolio of risk reduction strategies to maximize transportation safety and efficiency.

Although the importance of risk-based rail defect inspection scheduling has been recognized by railroads (*6, 11*). limited prior research has been conducted to optimize the scheduling of rail inspection as a means to reduce hazardous materials transportation risk. This research is developed to achieve the following objectives:
- Develop a novel model to quantify hazardous materials release risk by rail inspection frequency on a given hazmat route
- Develop a practical and applicable decision support tool to optimize rail inspection frequency at different track segments
- Provide new insights regarding broken rail prevention for reducing hazardous materials release risk

The exposition of this paper is as follows. First, a literature review is performed to understand the formation, growth and detection of rail defects and their impact on railroad transportation safety. Second, a new methodology is developed to quantify the relationship between hazmat release risk and rail defect inspection frequency. Third, the methodology is applied to an actual hazmat route and a decision support tool is developed to optimize the rail defect inspection schedule of specific track segments. Finally, we discuss the contributions and implications of this research to the literature and practice.

2   LITERATURE REVIEW
There are various approaches to reduce the risk of rail transport of hazardous materials, including enhancement in packaging and tank car safety design (*13-17*), deployment of rolling stock condition monitoring technologies (*18-20*), improvement in infrastructure (*21, 22*), routing (*23-25*), reduction of train speed (*26*), optimization of hazmat car marshaling (*27-30*), and improvement in emergency response practices (*31*).

Broken rail prevention has been identified as a promising risk reduction strategy (*2-6*). However, no previously published research has quantified the relationship between hazardous materials release risk and specific broken rail prevention techniques, particularly rail defect inspection as discussed in this paper. Ultrasonic technology is the primary rail defect detection method used by U.S. railroads. However, no feasible detection technology is capable of detecting all types of rail defects. Consequently, some defects remain undetected until growing to critical size and causing a broken rail. Fortunately, the majority of broken rails can be identified by visual inspection or track circuits (*32*). Thus, only a small percentage of broken rails result in train derailments (ca. one derailment per 100 broken rails) (*33*).

Rail defect inspection frequency affects the occurrence of broken rails, thereby affecting the corresponding hazardous materials release risk. In the next section, a model is developed to quantify route-specific broken-rail-caused hazmat release risk by rail inspection frequency.

3   BROKEN-RAIL-CAUSED HAZMAT RELEASE RISK BY INSPECTION FREQUENCY

In the context of rail transport of hazardous materials, release risk is defined as a product of hazmat car derailment rate, traffic exposure, conditional probability of release (CPR) and consequence of a release (*4,5,21, 22, 25, 26*):

$$R = Z_b \times M \times P \times C \tag{1}$$

where:

 R   = broken-rail-caused hazmat release risk
 Z_b = broken-rail-caused car derailment rate per traffic exposure
 M   = hazmat traffic exposure
 P   = conditional probability of release of a derailed hazmat car
 C   = consequence of a release (e.g. population in the affected area)

Broken-rail-caused car derailment rate can be estimated as a product of broken rail rate, the percentage of broken rails causing derailments, and the average number of cars derailed per broken-rail-caused derailment (*34*).

$$Z_b = S \times \theta \times D_b \tag{2}$$

where:

 S   = number of broken rails per million gross ton-miles
 θ   = percentage of broken rails causing train derailments
 D_b = average number of cars derailed per broken-rail-caused train derailment

Furthermore, broken rail rate per million gross ton-miles is estimated using the following equation:

$$S = \frac{B(K)}{T} \tag{3}$$

where:

 B(K) = number of broken rails per track-mile by rail inspection frequency
 K   = annual rail defect inspection frequency
 T   = annual traffic density, in million gross tons (MGT)

The number of broken rails per mile, B(K), can be estimated using the engineering model developed by the U.S. Department of Transportation (U.S. DOT) Volpe Transportation Systems Center based on more than two-decades of rail integrity research (*9, 10*):

$$B(K) = \sum_{i=1}^{K} \left\{ M \times \frac{e^{-\left(\frac{N_{i-1}}{\beta}\right)^{\alpha}} - e^{-\left(\frac{N_{i-1}+X_i}{\beta}\right)^{\alpha}}}{1 + \lambda\left(\frac{T}{K} - \mu\right)} \times \lambda\left(\frac{T}{K} - \mu\right) \right\} \tag{4}$$

where,

 M   = number of rail segments per mile, 273 (*10*)
 α   = Weibull shape factor, 3.1 (*36*)

β   = Weibull scale factor, 2150 (*36*)
λ   = slope of the number of rail breaks per detected rail defect (S/D) vs. inspection interval
            curve, 0.014 (*10*)
μ   = minimum rail inspection interval, 10 MGT (*10*)
N_{i-1} = rail age (cumulative gross tonnage on the rail) at the (i-1)th inspection, $N_i = N_{i-1} + X_i$

Route-specific broken-rail-caused hazmat release risk is estimated based on equations (1) to (4):

$$R_{route}(K) = \sum_{j=1}^{J} \left\{ \frac{B_j(K)}{T_j} \theta_j D_{b_j} M_j P_j C_j \right\} \qquad (5)$$

where, J is total number of track segments on a route. All other parameters are defined above.

A decision support tool (DST) is developed to automate the calculation process using the Visual Basic Application (VBA) platform in Microsoft Excel. Given rail information (rail age and annual rail inspection frequency), route information (traffic density, FRA track class, method of operation), tank car safety design and population density along the route, the model estimates broken-rail-caused hazardous materials release risk on each segment and over the entire route (Figure 2). The model first calculates the frequency of rail breaks per mile on each segment (Equation 4), then uses this to calculate broken-rail-caused tank car derailment rate (Equations 2 and 3). Based on tank car specification information and speed (varying by FRA track class), the conditional probability of release of a derailed tank car is estimated (*4*). Finally, route-specific hazmat release risk is evaluated (Equation 1) as the output.
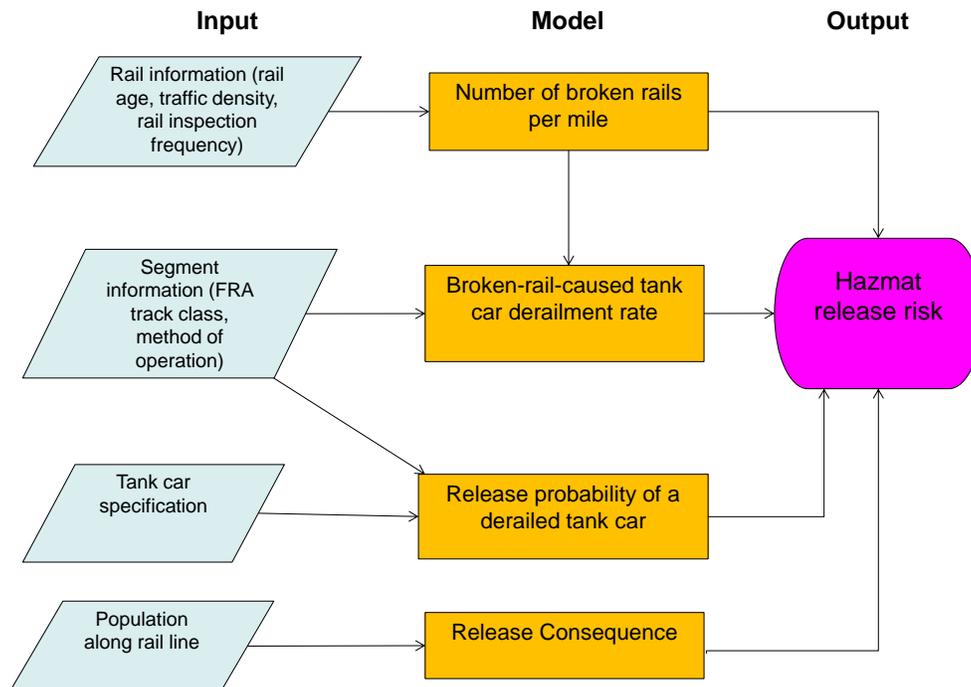

Figure 2 Decision support tool for assessment of hazmat release risk
by rail defect inspection frequency

An actual hazardous materials route is used as an example to illustrate the application of the methodology described above.

4 CASE STUDY

4.1 Route Information

An anonymous, actual hazmat route was considered in this study. The route information was analyzed and displayed on a geographic information system (GIS) platform. First, the route was generated using a routing software called PC-Miller | Rail 18 developed by ALK technologies based on origination, destination and a few en-route stations (*35*). Then, the route information was exported to a GIS platform using the Network Analyst tool in the GIS software ArcGIS (*36*). For each route segment, the FRA track class and method of operation were provided by railroad carriers using their internal databases. The population density along each track segment was estimated by linking U.S. Census data to route data based on geographic information (*26*) (Figure 3).
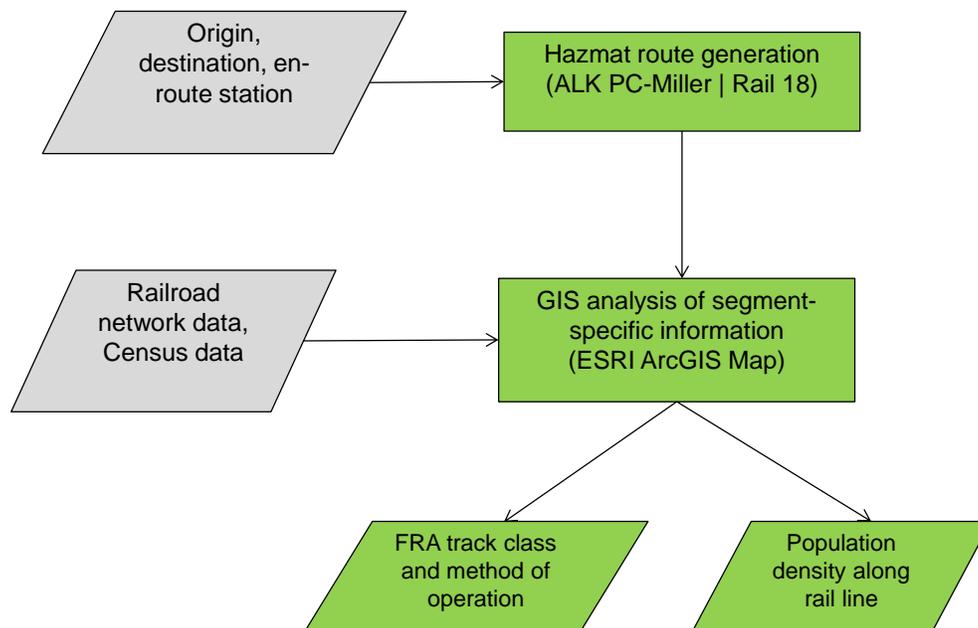

Figure 3 GIS analysis of route specific characteristics

The GIS analysis shows that the 2,273-mile route includes 1,194 track segments. The majority of the route segments are in signaled territories and are maintained to meet FRA Class 4 and Class 5 standards). The five principal track classes commonly used by U.S. freight railroads, ranging from class 1 with the lowest maximum speed (10 mph) to class 5 with the highest (80 mph), correspond to specifications for track structure, geometry, and inspection frequency and method that alter the likelihood and severity of derailments. Using U.S. Census data, the average population density along this route is 349 people per square mile (Table 1).

Table 1 Hazmat route information

	Value
Total Length (Miles)	2,273
Number of Segments	1,194
Distribution of Track Class (%)	
Class 1	1.1%
Class 2	2.2%
Class 3	14.2%
Class 4	46.1%
Class 5	36.4%
Method of Operation (%)	
Non-Signaled	6.9%
Signaled	93.1%
Average Population Density per Square Mile	349

4.2   Parameter Estimation

In addition to route information, the model implementation is based on the following parameters:

1) Percent of broken rails that cause derailments, θ
2) Average number of cars derailed per broken-rail-caused freight-train derailment, D_b
3) Conditional probability of release of a derailed tank car, P
4) Consequence of a release incident, C

4.2.1   Percent of broken rails that cause derailments, θ

This parameter may vary depending on track characteristics, environmental factors, and the type and location of rail defects (*33*). The percentage of broken rails causing train derailments may be greater in a non-signaled track territory due to a lack of track circuits (*4*). In this paper, based on the prior research, we assume that 1% of rail breaks cause derailments in a non-signaled track versus 0.5% in a signaled track (*9, 10, 33*).

4.2.2   Number of cars derailed per broken-rail-caused freight-train derailment, D_b

On average, a broken-rail-caused freight-train derailment on higher track classes (Class 3 to Class 5) causes 16 cars derailing, whereas the derailment severity is 9 cars derailed on lower track Classes 1 and 2 (Figure 4). The greater number of cars derailed on higher track classes may be associated with the higher maximum allowable train speeds (*2*).
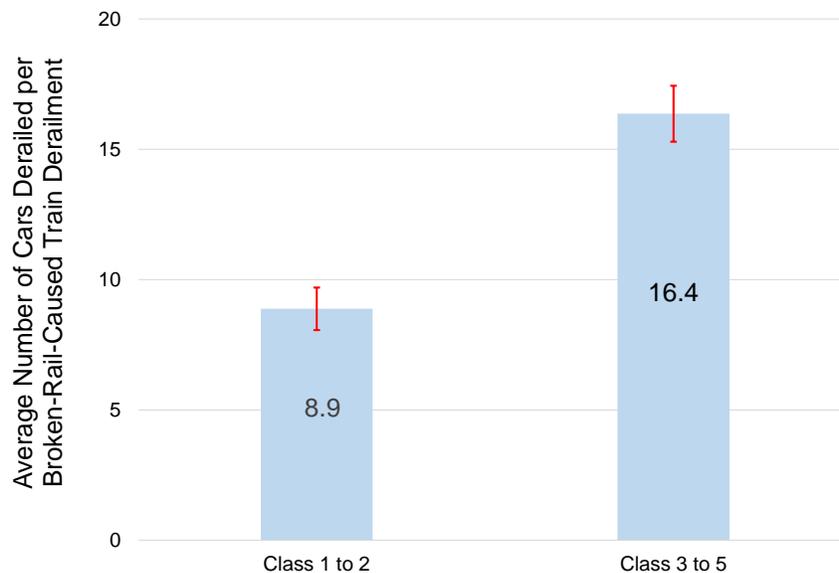
Figure 4 Broken-rail-caused freight-train derailment severity by FRA track class, Class I mainlines, 2001 to 2010 (error bars represent 95% confidence interval)

4.2.3   Conditional probability of release of a derailed tank car, P

Conditional probability of release (CPR) of a derailed tank car reflects its safety performance in accidents (*16, 17*). Previous studies found that the CPR varies by tank car specification (*15-17, 37*) and derailment speed (*21, 26*). Table 2 presents the CPR function for the most common types of tank cars in the United States (*4*). For example, for the 111A100W1 tank car, the speed-dependent CPR function is 0.0096S (S is derailment speed). If derailment speed is 25mph, the CPR of this tank car is 0.0096×25 = 0.24. This means that the probability that a derailed 111A100W1 tank car releases is 0.24. When speed is reduced from 25 mph to 24 mph, the CPR is expected to decrease from 0.24 to 0.2304 (0.0096×24 = 0.2304). The reduction of CPR (0.24-0.2304 = 0.0096) is equal to the slope parameter A (0.0096).

TABLE 2 Estimated speed-dependent conditional probability of release (CPR) by tank car specification, grouped by CPR function (*4*)

Stenciled Specification	Speed-Dependent CPR (A×S)	Percentage in Fleet
111A100W1	0.0096S	51.04%
111A100W3	0.0096S	5.72%
111A100W2	0.0096S	4.51%
211A100W1	0.0096S	4.17%
111A100W5	0.0096S	3.35%
112J340W	0.0018S	13.54%
105J300W	0.0018S	4.25%
112J400W	0.0018S	1.92%
105J400W	0.0018S	1.84%
105J500W	0.0012S	2.77%
Other		6.90%
Total		100.00%

4.2.4   Consequence of a tank car release incident, C

Release consequence can be evaluated by several metrics, including property damage, disruption of service, environmental impact, human impact (e.g., number of people potentially exposed to a release), litigation or other types of impacts (*26*). Among these consequence measures, population in the affected area (to be protected or evacuated) was often used in previous studies (*4, 5, 21, 26, 38*). The hazard exposure model provided in the U.S. DOT Emergency Response Guidebook (ERG) includes recommendations for the calculation of affected area (*39*). Once the affected area is determined, the number of people affected can be estimated by multiplying the affected area by the average population density within the affected area (*26*). In this paper, we assume the affected area is a 0.5-mile-radius circle based on the ERG recommendation for a flammable hazmat transported on the route (Figure 5).
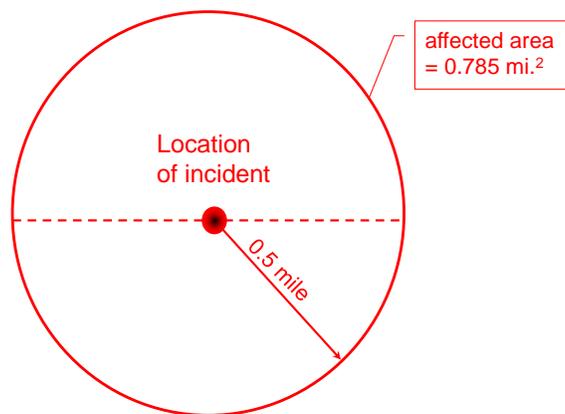

Figure 5 Affected area based on U.S. DOT Emergence Response Guide recommendation

4.3   Baseline Risk

It is assumed that the rails on this route are inspected three times per year. The average rail age is 500 MGT, annual traffic density is 80 MGT and tank car type is 111A100W1. Using the decision support tool described above, the baseline risk on this route is 3.28E-02 per carload. It is interpreted as the expected number of persons affected (to be protected or evacuated) per tank car shipment on this route. For every 100 tank carloads, there is an average of three persons affected by potential hazmat release incidents (0.0328×100=3.28).

5   RISK REDUCTION

This section addresses risk reduction by optimizing the rail inspection schedule. One important feature of railroad hazmat route risk is that a small proportion of mileage could account for the majority of risk. For example, on the studied route, 18% of the track miles accounted for 80% of the total route risk (Figure 6).
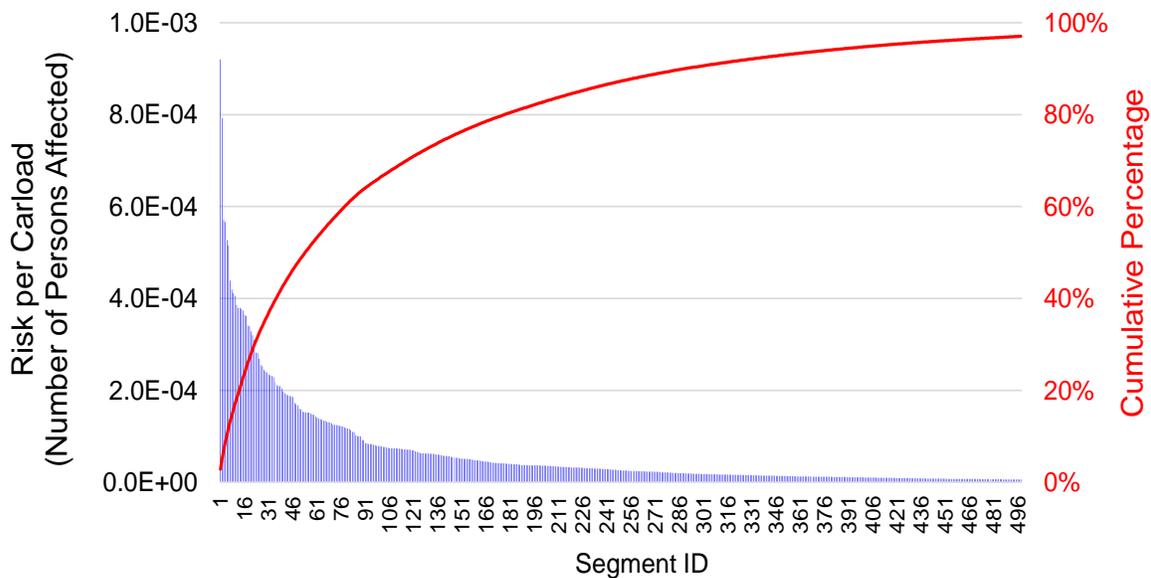

Figure 6 Broken-rail-caused hazmat risk distribution by segment
(a portion of the entire distribution is displayed)

Because certain locations have much higher risks than others, it is important to identity these "risk hot spots" on a given hazmat route and develop efficient strategies to mitigate their risks.

5.1   Risk Hot Spot Identification

The segment-specific risk is categorized using Jenks optimization method. This method minimizes the variation of values within the same category, and maximizes the discrepancy between different categories (*40*). This paper classifies the risk into three categories since each category accounts for similar amount of total risk (Figure 7). Table 3 illustrates the number of segments, mileage and risk within each risk category. It shows that 23 track segments with the highest risk (2.8E-4 to 9.2E-4 per carload) or only 4% of route length accounted for 31% of the total route risk.

TABLE 3 Segment Risk Classification

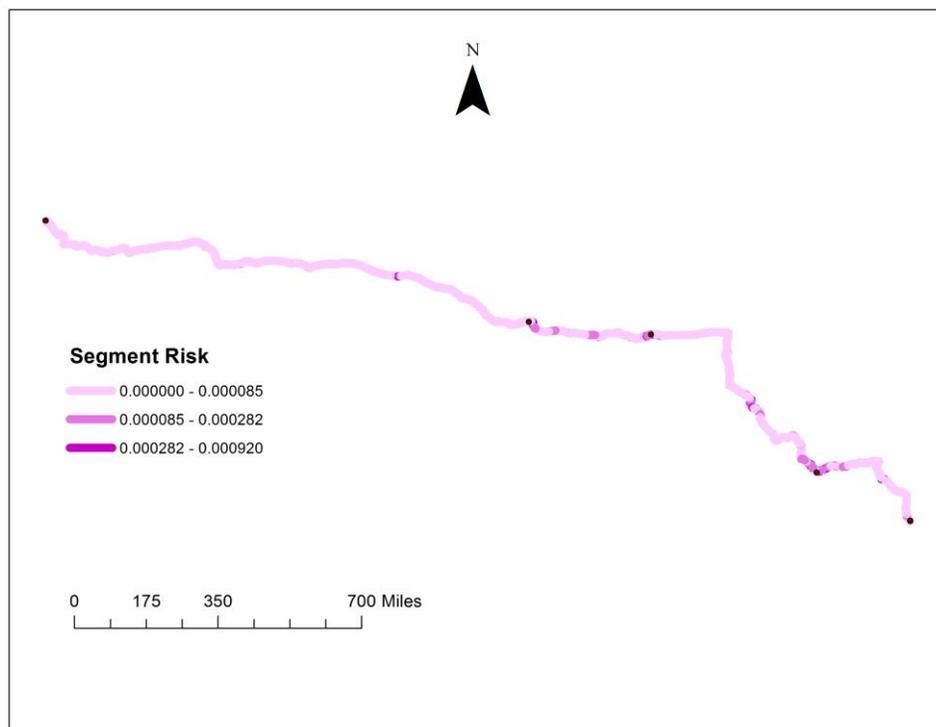| Risk Category	Number of Segments	Percentage of Total Mileage	Percentage of Total Risk
Low (0 to 8.5E-5)	1,074	87%	36%
Medium (9E-5 to 2.8E-4)	67	9%	33%
High (2.8E-4 to 9.2E-4)	23	4%	31%
Total	1,164	100%	100%

Figure 7 Broken-rail-caused hazmat release risk by track segment

5.2   Pareto-Optimization of Rail Defect Inspection Frequency

One potential strategy to reduce the risk of rail transport of hazardous materials is the optimization of rail defect inspection frequency. For illustration, within each risk category specified above, we consider six possible annual inspection frequencies, ranging from 2 to 7. There is a total of 216 (3^6=216) combinations of rail inspection schedules. The baseline scenario is that all track segments are inspected three times per year, denoted as (3, 3, 3). There are a number of alternative inspection schedules. An example alternative may be as follows: the low-risk track segments are inspected three times per year, medium-risk tracks receive four inspections per year and high-risk tracks are inspected six times per year. This example scenario is denoted as (3, 4, 6). The estimated broken-rail-caused hazmat release risk and total mileage inspected given each possible rail inspection schedule are quantified and plotted (Figure 8a). Given the same total miles inspected, some inspection schedules result in lower risks. These "optimal" schedules constitute a Pareto frontier (Figure 8b). The Pareto frontier represents the optimal scheduling of rail defect inspection frequency given a total mileage to inspect. For example, if the rail operator has the ability to inspect 7,067 miles per year, the optimal schedule is to inspect the low-risk tracks three times a year, the medium-risk tracks four times per year and high-risk tracks six times per year. The route risk in this scenario is 3.06E-04. Compared to the baseline scenario (all tracks are inspected three times per year) that is also on the Pareto frontier, the route risk reduces by 7% and total mileage inspected increases by 4%. The Pareto frontier demonstrates the "optimal" scheduling given resource constraint. Ultimately, a multi-attribute decision model can be developed to determine the inspection frequency based on the decision maker's preference over the risk and cost (mileage tested as a proxy) and the trade-off between these attributes.
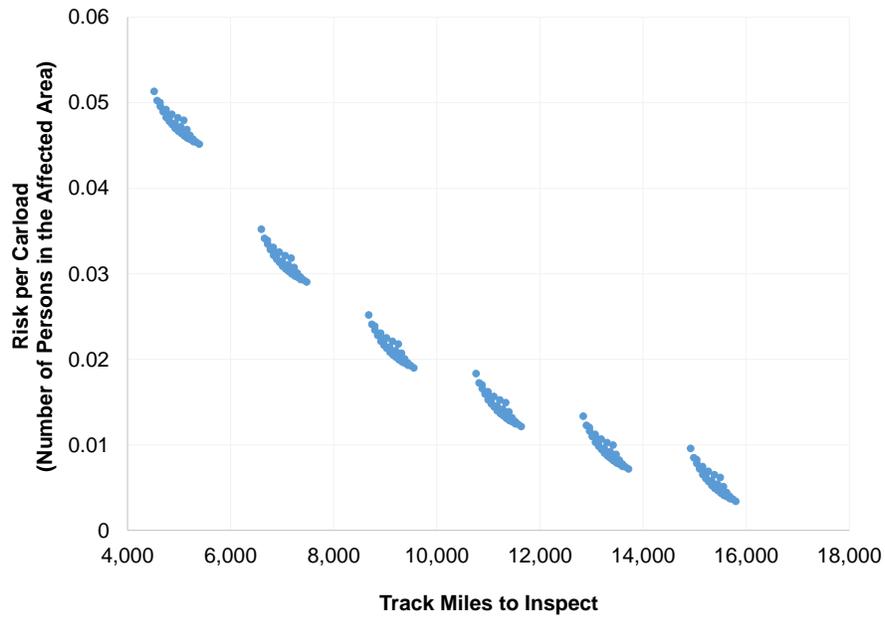
(a)
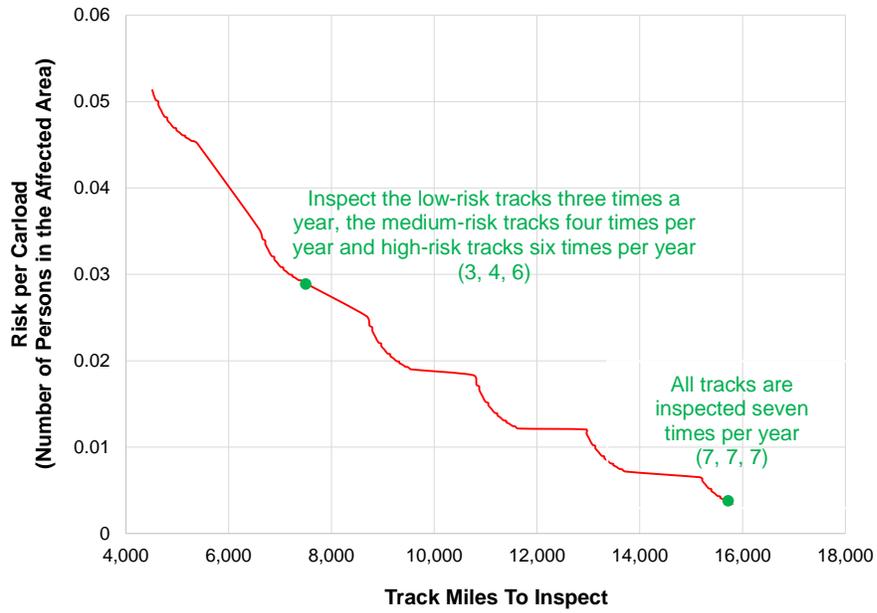
(b)

Figure 8 Broken-rail-caused hazmat risk by total miles to inspect
(a) all possible inspection schedules; (b) Pareto-optimal schedules

6   DISCUSSION

This research develops a new methodology to evaluate broken-rail-caused hazmat release risk by annual rail defect inspection frequency. The analysis shows that more frequent rail inspection is expected to reduce the occurrence of undetected rail defects, thereby reducing broken rails and the corresponding hazmat release risk from broken-rail derailments (Figure 9). For illustration convenience, the analysis in Figure 9 assumes that all track segments receive the same frequent inspections. The model can be adapted to account for segment-specific inspection frequency as discussed above. Furthermore, the model can be further developed to quantify the effectiveness of a number of other broken rail prevention techniques (e.g., improving detection accuracy, adding circuits to non-signaled track territories etc.) for reducing hazmat release risk. Ultimately, this could lead to development of an integrated infrastructure management framework to reduce train accidents, thereby reducing accident-caused hazmat release risk.
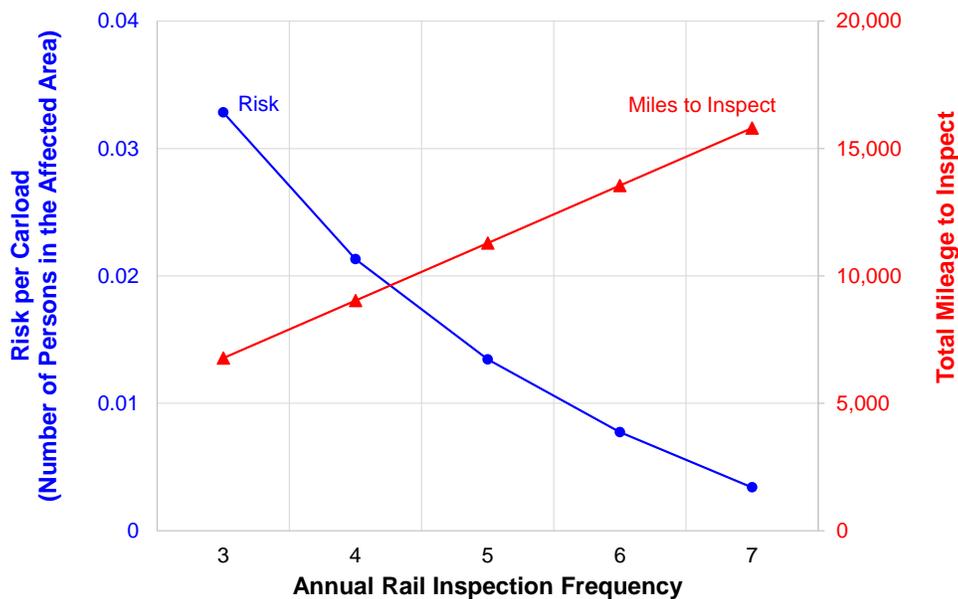

Figure 9 Risk reduction by increasing annual rail inspection frequency
(note: all five inspection frequencies are Pareto-optimal)

In addition, the decision support tool developed in this paper integrates accident, traffic, infrastructure and geographic information from various databases, implements a complicated algorithm and yields recommended decision solutions. The tool has the interface to be integrated with railroad enterprise infrastructure maintenance systems to enable a better-informed decision process in order to cost-efficiently manage hazardous materials release risk.

7   CONCLUSION

This research is the first study focusing on assessing the relationship between broken rail risk and hazmat release risk. Increased rail inspection frequency reduces the occurrence of rail breaks, thus reducing broken-rail-caused hazmat release risk. The model is used on an actual hazmat route and demonstrates the safety effectiveness of optimizing rail inspection frequency for risk reduction. The case study illustrates how increased inspection frequency on a small number of high-risk segments can significantly reduce the overall route risk with a minimal increase in required resources. The model can be further developed and incorporated into a railway hazmat transportation risk management framework for improving transportation safety in the most cost-efficient manner.

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