Analysis of Freight Train Collision Risk in the United States

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ABSTRACT

Rail plays a key role in the transportation of hazardous materials (hazmat). Improving railroad hazmat transportation safety is a high priority for both industry and government. Many severe railroad hazmat release incidents occur due to train accidents. The Federal Railroad Administration identifies over three hundred accident causes, including infrastructure defects, rolling stock failures, human factors, and other causes. Understanding how hazmat transportation risk varies with accident cause is a key step in identifying, developing, evaluating, and prioritizing cost-justified accident prevention strategies, thereby mitigating hazmat transportation risk. The objective of this paper is to develop an integrated, generalized risk analysis methodology that can estimate accident-cause-specific hazmat transportation risk, accounting for various train and track characteristics, such as train length, speed, point of derailment, the number and placement of tank cars in a train, tank car safety design, and population density along rail lines. Using the two major causes of accidents on freight railroads – broken rails and track geometry defects – as an example, we demonstrate a step-by-step analytical procedure and decision support tool to assess how accident frequency, severity, and hazmat transportation risk vary by accident cause. The research method can be adapted for risk analysis at corridor- or network-level accounting for other accident causes.

Keywords: Hazardous Materials; Railroad; Risk Analysis; Accident Cause

1 INTRODUCTION

Rail transports over two million carloads of hazardous materials (hazmat) in the United States annually. Unlike a truck trailer that carries a single hazmat car, a train can carry multiple hazmat cars (e.g. 50 to 120 flammable liquid cars) with greater transportation efficiency. Although over 99.99% of rail hazmat shipments are safe, a train accident may result in the derailment and release of multiple tank cars.

There are three principal strategies to reduce hazmat transportation risk, which are the 1) prevention of tank car derailment in the first place; 2) mitigation of its release probability by tank car safety improvement; or the 3) mitigation of release consequences. While prior research has largely focused on the latter two strategies, there has been relatively less work with respect to reducing tank car derailment probability. One risk management strategy in this category is reducing train derailment likelihood by preventing major accident causes. The objective of this paper is to develop an accident-cause-specific railroad hazmat transportation risk analysis model, that is adaptable to a variety of infrastructure-related, train-related, and operational factors. The model outputs the amount of risk due to a specific accident cause. The model can assist decision makers in the evaluation of the effect of a particular accident cause on hazmat transportation risk.

2 LITERATURE REVIEW

Prior research related to train derailment risk has covered many aspects of the situation including the wheel-rail interaction (*1*), derailment causal analysis (*2,3*) and hazmat transportation risk (*5-8, 28-31, 35*). These studies have focused on various risk mitigation strategies, related to infrastructure (*5, 8*), rolling stock (*9*), tank car safety enhancement (*10-12*), train makeup (*13, 14*), or mitigation of release consequence (*15*). Each of these risk reduction strategies focuses on at least one event in the causal chain of an accident-caused release incident (Table 1).

TABLE 1 Risk Management Strategies and Risk Factors

2.1 Train Accident Occurrence

Many severe hazmat release incidents are due to train accidents, particularly train derailments. Derailments account for over 72 percent of all types of accidents on freight railroads (*22*). The Federal Railroad Administration (FRA) of the U.S. Department of Transportation (USDOT) identifies around 389 distinct accident causes (*21*) related to infrastructure, rolling stock, human factors, and other factors (*23*). Prior research found that over 70 percent of freight train mainline derailments were caused by either infrastructure defects or rolling stock failures (*23*). The hazmat risk reduction strategies include the prevention of track defects (*8*), equipment condition monitoring to reduce in-service failures (*4*), or the use of more advanced train control technologies to reduce human error (*24*).

2.2 Number of Cars Derailed

The total number of cars derailed depends on accident cause, speed, train length, and point of derailment (*25, 27*). The number of cars derailed (a proxy indicator of accident severity) is an important consideration.

2.3 Number of Hazmat Cars Derailed

The total number of hazmat cars derailed is related to train length, number of hazmat cars and non-hazmat cars in a train, and their placement (*27, 36*). Possible strategies for reducing the probability of tank car derailment include reducing the speed of the train in order to reduce the total number of vehicles derailed (*28*) and the placement of tank cars in the positions that are less likely to derail (*13, 14*).

2.4 Number of Hazmat Cars Releasing Contents

Not all derailed or damaged tank cars release their contents. A tank car accident database has been developed by the Railway Supply Institute (RSI) and the Association of American Railroads (AAR). Using this database, it has been found that the tank car release probability can be reduced by using more robust tank car designs (*10-12*). In addition, reducing train speed can reduce the accident impact on the tank car, hence decreasing release probability (*28*).

2.5 Release Consequences

The consequences of a release can be measured with different metrics, such as property damage, environmental impact, traffic delay, or the affected population. The Geographical Information System (GIS) can be used for consequence analysis when integrated with other databases such as census and rail network data (*29*). The use of a lower-hazard chemical, rerouting of hazmat traffic to avoid populated areas or improved emergency response and evacuation have been identified as potential strategies to mitigate release consequences, thereby reducing the risk (*30*).

2.6 Knowledge Gaps

While the prior research recognized the importance of evaluating hazmat transportation risk on the causal level, they exclusively used empirical data analyzing approaches for this purpose. This paper aims to build a probabilistic risk analysis methodology that can estimate accident-cause-specific hazmat transportation risk using statistical approaches. Ultimately, this paper aims to address how railroad hazmat transportation risk varies by major causes given specific track and train characteristics. This information can further support the identification and prioritization of alternative risk mitigation strategies, particularly accident cause prevention techniques.

3 DATA SOURCES

The Rail Equipment Accident/Incident Report (REAIR) form is used by railroads to report all accidents that exceed a monetary threshold of damages to infrastructure and rolling stock. FRA compiles these reports into the Rail Equipment Accident (REA) database, which records accident type, consist type, track type, accident cause, accident consequence and other information. In this paper, the FRA REA database is used to calculate the frequency of freight-train derailments on Class I railroad main tracks. In addition, the FRA Operational Database is used to calculate traffic volume, in terms of train-miles. Based on these two databases, we can calculate accident-cause-specific derailment rate (number of derailments normalized by traffic exposure) and derailment severity (e.g., the number of cars derailed per derailment). Furthermore, the conditional probability of release (CPR) for a derailed tank car, which reflects its safety performance, is obtained based on published statistics from the Association of American Railroads and Railway Supply Institute.

4 METHODOLOGY

The research methodology portrays the process of an accident-caused release incident. Each event in this process is subject to specified influencing factors. We develop a Probabilistic Risk Analysis (PRA) model that integrates a set of probabilistic processes to calculate the probability of a release incident (Figure 1). This paper focuses on accident-caused release, without accounting for releases due to thermal tearing. The latter will be addressed through a separate study in the next step.

FIGURE 1 Accident-cause-specific hazmat release risk analysis framework.

4.1 Train Derailment Rate Calculation

Train derailments account for the majority of accident-caused release incidents, and thus, this paper focuses on mainline derailments. The derailment rate is defined as the number of derailments normalized by traffic exposure:

$$Z = \frac{\mathrm{Y}}{\mathrm{M}} \tag{1}$$

Where,

Y = number of train derailments

M = traffic exposure

4.2 Tank Car Derailment Probability

Position-dependent tank car derailment probability is related to its position in a train, the point of derailment (the first car in a sequence of cars derailed per accident), and the number of cars derailed. In this paper, “cars” refers to all types of vehicles in a train (locomotives as well as empty and loaded railcars) unless stated otherwise (*7, 34*). Equation (2) presents a probabilistic model to estimate the derailment probability of a tank car at a given position of a train on a specific track segment.

$$PD_i(j) = \sum_{k=1}^{j} \left\{ POD_i(k) \times \sum_{x=j-k+1}^{L-k+1} PN_i(x) \right\} \tag{2}$$

Where,

$PD_i(j)$ = probability of derailment for a vehicle at the jth position of a train on the ith segment

$POD_i(k)$ = point of derailment probability for the kth position of a train on the ith segment

$PN_i(x)$ = probability of derailing x vehicles in a train accident on the ith segment

L = train length (total number of vehicles in the train, including locomotives)

4.3 Release Probability of Derailed Tank Car

Tank car safety performance is reflected by its release probability once being derailed or damaged. This probability is referred to as the conditional probability of release (*7*), denoted by $CPR_i(j)$. Assuming that the releases of tank cars are independent, the probability that at least one hazmat tank car releases, denoted by $P_i(X_R|TD)$, is equal to one minus the total probability that none of the derailed tank cars release contents:

$$P_i(X_R|TD) = \left\{ 1 - \prod_{j} [1 - PD_i(j) \times CPR_i(j)] \right\} \tag{3}$$

Where,

$P_i(X_R|TD)$ = probability of a release incident after a train is derailed on the ith segment
$CPR_i(j)$ = conditional probability of release (CPR) of a derailed tank car

4.4 Hazmat Transportation Risk

In the transport of hazardous materials, segment-level risk is generally defined as the multiplication of the probability of a release by the consequence of a release. Route risk is the summation of segment risk.

$$\mathrm{R} = \sum_{i=1}^{N} P_i C_i \tag{4}$$

Where,
R = hazardous material transportation risk (e.g. expected release consequence)
P_i = probability of a release incident on ith track segment
C_i = consequence of a release (e.g. affected population) on ith segment
N = number of segments

Segment-specific release probability (P_i) per train shipment can be estimated as follows:

$$P_i = P_i(TD) \times P_i(X_R|TD) \ \approx (Z_i L_i) \times \ P_i(X_R|TD) \tag{5}$$

Where,
$P_i(TD)$ = probability of a train derailment when traversing the ith segment
$P_i(X_R|TD)$ = probability of a release incident after a hazmat train is derailed on the ith segment
Z_i = train derailment rate on the ith segment
L_i = segment mileage

5 PARAMETER ESTIMATIONS IN RISK MODELING

5.1 Freight-Train Derailment Rate

This paper focuses on freight train derailments on Class I railroad mainlines, excluding other types of accidents (e.g. collision or grade crossing accidents). Table 2 shows that the number of derailments and number of cars derailed vary with accident cause. This paper focuses on major cause groups. For illustration, this paper concentrates on the two most common freight-train derailment causes, which are broken rails and track geometry defects, respectively. We use the top two causes as examples because they collectively account for around 20 percent of all freight-train derailments on Class I mainlines (*23*). However, the generic probabilistic risk analysis methodology developed herein can be adapted to other causes as well.

TABLE 2 Class I Mainline Freight Train Derailments due to Major Causes, 2000 to 2016

The train derailment rate is affected by a number of factors, such as FRA track class, method of operation, and annual traffic density (*31*). This analysis focuses on FRA track class, which has been identified as a key influencing factor (*20, 25, 31, 33*). There are five principal track classes commonly used by U.S. freight railroads, ranging from Class 1, with the lowest maximum allowable freight train speed (10 mph), to Class 5, with the highest (80 mph in signaled territory). These classes include specifications for track structure, geometry, inspection frequency, and method of inspection, with more stringent requirements for higher track classes.

The FRA standards represent minimum requirements; in fact, railroads can maintain various sections of their infrastructure to standards that exceed the minimum required by the FRA. We do not further delineate accident statistics according to additional factors in order to avoid a small sample size that will cause statistical sampling biases (*7*). Future research can account for additional factors affecting the train derailment rate. Track-class-specific train-mile distribution (track class 1 – 0.8%; class 2 – 3.3%; class 3 – 11.1%; class 4 – 54.7%; class 5 – 30.0%) is presented in a previous study using traffic data from Class I railroads (*26*).

The derailment rates caused by broken rails and track geometry defects by FRA track class were calculated (Figure 2). Future research may consider alternative traffic exposure metrics, such as car-miles or ton-miles on each track class, when the information is available. Figure 2 shows that the FRA track class has an inverse relationship with the train derailment rate for both broken rails and track geometry defects. This is probably attributable to better infrastructure conditions and more frequent inspection and maintenance on these high track classes, thereby reducing accident probability. Also, on each track class, broken rails result in a higher freight-train derailment rate than track geometry defects. The derailment rate heterogeneity by accident cause and FRA track class is considered in our risk model.

FIGURE 2 Accident-cause-specific train derailment rate by FRA track class.

For the Class 1 mainline freight train derailment rate from 2000 to 2016, we found an average annual decline rate of 10.6% and 8.7%, due to broken rails and track geometry defects, respectively (Figure 3). Assuming that this trend continues, these percentages can be used as temporal adjustment factors to estimate the derailment rate for a future year. A similar adjustment methodology has been used in the literature (*37*). In our study, the reference year can be 2008, since its derailment rate is closest to the 17-year average. Other analysts can also use our approach to update derailment rate statistics using future data.

FIGURE 3 Class I mainline freight train derailment rate from 2000 to 2016.

5.2 Number of Cars Derailed

The model assumes that the number of cars derailed (both loaded and empty railcars, including locomotives) follows a truncated geometric distribution (*25*, *26*). In Equations 6 and 7, $PN(x)$ represents the probability of derailing a certain number of cars in a derailment, and x is the number of cars derailed or damaged. The probability of each car derailment, P, is affected by derailment speed and residual train length.

$$PN(x) = \frac{P(1-P)^{x-1}}{1-(1-P)^{RL}} \tag{6}$$

$$\mathrm{P} = \frac{\mathrm{e}^{\mathrm{z}}}{1+\mathrm{e}^{\mathrm{z}}} \tag{7}$$

In terms of train derailment severity analysis, the response variable is the total number of cars derailed per accident. A truncated geometric (TG) regression model was developed; accounting for derailment speed, residual train length (RL = L-POD+1), proportion of loaded cars (LO), and whether the POD is loaded (I(POD)) as the explanatory variables. The fitted model is based on data covering Class I mainline freight-train derailments between 2000 and 2016 for broken rails and track geometry (Equations 8, 9). The modeling details can be found in (*25*, *26*).

$$z\ (broken\ rails) = logit(P) = \log\left(\frac{P}{1-P}\right) \\ = -0.891 - 0.387 \times IPOD - 0.085 \times DS^2 \tag{8}$$

$$z\ (track\ geometry\ defects) = logit(P) = log\left(\frac{P}{1-P}\right) \\ = (2.406 + 1.242 \times DS - 0.343 \times LO - 0.401 \times DS^2) \tag{9}$$

Where,

DS = logarithmic derailment speed (the speed is in miles per hour)

I(POD) = whether the POD is a loaded car (1 indicates that the POD is loaded, 0 otherwise)

LO = proportion of loaded cars to total number of cars (between 0 and 1, where 0 denotes an entirely empty train and 1 denotes a fully loaded train)

5.3 Point of Derailment

The normalized point of derailment (NPOD) is a metric accounting for train length heterogeneity. It equals to the POD divided by train length (between 0 and 1). Beta distribution was found to be the best fit for FRA-reportable derailment data between 2000 and 2016 on mainlines. Given a train length L, the probability that the POD is at the kth position, POD(k), can be estimated using the following equation:

$$POD(k) = F\left(\frac{k}{L}\right) - F\left(\frac{k-1}{L}\right) \tag{10}$$

Where,

POD(k) = POD probability at the kth position of a train

F() = cumulative density distribution of the fitted NPOD distribution

L = train length (total number of cars in a train)

Figure 4 shows the cumulative POD distribution for derailments caused by broken rails and track geometry defects. It shows that the POD in a broken-rail-caused derailment is more likely to occur near the front of the train, whereas PODs caused by track geometry defects are relatively more uniformly distributed. This finding is consistent with a prior study based on older datasets (*7*).

FIGURE 4 Fitted NPOD distributions by major accident causes.

6 DECISION SUPPORT TOOL

As part of this research, an automatic risk decision support tool is being developed (Figure 5). This tool is comprised of built-in formulae (presented in Sections 4 and 5) required for calculating the cause-specific release probability of hazmat tank cars on Class I freight railroad mainlines. The tool is flexible enough to account for various risk factors (such as derailment speed, residual length, position of hazmat car, etc.). A numerical example will be provided in Section 7 to demonstrate the practical use of the tool for route-specific risk assessment.

FIGURE 5 Implementation of decision support tool.

This computer tool has two practical advantages. First, it can automate sophisticated risk analysis processes based on user-defined inputs. Second, it can be further developed and used to compare alternative risk reduction strategies on specific routes or networks. Under various "what-if" scenarios, the tool can generate different risk profiles, thereby providing guidance for data-driven risk management.

7 NUMERICAL EXAMPLE

7.1 Position Dependent Derailment Probability

In this section, we present a numerical example to explain the practical use of the methodology described above. For illustrative convenience, we focus on broken rails and track geometry defects. The methodology can be adapted to other causes. In this paper, we assume 100 vehicles per train including locomotives, hazmat, and non-hazmat railcars, but the train length can be altered as desired. The position-dependent vehicle derailment probability can be estimated using Equation 1. Accident-cause-specific vehicle derailment probabilities depending on position are presented below for comparison. Given the train length (in our example, 100), the probability of derailment is estimated to vary with speed. The selected speeds (10, 25, 40, 60, and 80 mph) represent the maximum allowable speeds by FRA track classes 1 to 5, in signaled track territory.

FIGURE 6 Position-dependent car derailment by accident cause.

For a given position of a tank car in a train, the higher the speed, the more likely that the car will be derailed (Figure 6). For example, consider a tank car located at the 40th position of a train, in which its derailment probability is 0.13 if this train is derailed at 25 mph, due to a broken rail. By comparison, the derailment probability is estimated to be 0.079 in a track-geometry-caused derailment at 25 mph. At 60 mph, the derailment probabilities increase to 0.318 and 0.123 for each cause, respectively. Moreover, we can see that, all else being equal, the vehicle derailment probability for broken rails is higher than for track geometry defects, because on an average, broken rails tend to derail more cars than track geometry defects (*16, 19*).

7.2 Position-Dependent Release Probability per Train-Mile

Table 3 shows derailment and release probabilities per train-mile for both accident causes, by FRA track class. It is assumed that all tank cars conform to DOT 117 standards, with the estimated conditional probability of release being 0.029 (*37*). We also conservatively assume that the accident speed is the maximum track speed for each track class. It is assumed that 10 hazmat cars are placed in the "worst case" scenario, where these cars are located in positions that are more likely to derail. A sensitivity analysis of the effect of tank car position will be shown later.

TABLE 3 Train Derailment and Release Probability by Accident Cause

Table 3 shows that a higher FRA track class has a lower release probability per train-mile for each cause. The higher the track class, the lower the derailment rate caused by either broken rails or track geometry defects (as shown in Figure 2). FRA track class has a dual effect on derailment rate and tank car release probability. On one hand, a higher track class has a lower train derailment rate caused by broken rails or track geometry failures. On the other hand, a higher track class has a higher maximum operating speed, thus may increase the probability of tank car derailment and release (*37*). Because the decline in train derailment rate more than offsets the increase of tank car derailment and release probabilities, the net result is that higher track classes are associated with lower hazmat release probabilities per train-mile. Using broken rails as an example, the hazmat release probability per train-mile on track class 3 is approximately twice of that on track class 4, and six times of the release probability on track class 5, respectively.

7.3 Effect of Tank Car Positions

Previous studies have suggested that the tank car derailment probability is affected by its position in the train. Therefore, change of tank car position was identified as a potential risk reduction strategy *(32)*. In the example above, we considered the worst-case scenario. In this subsection, we conducted a severity analysis for two additional tank car placement scenarios. The "best" scenario is one in which all the hazmat tank cars are placed in positions with the lowest probabilities of car derailment in an accident. In the "random" scenario, all hazmat cars are placed randomly throughout the train. Similar to the analysis above, higher track classes have lower release probabilities for given tank car placement. On the same track class, release probability per train-mile varies by tank car positions (Figure 7).

FIGURE 7 Hazmat release probability per train-mile by accident cause.

7.4 Route Transportation Risk Calculation

This section discusses how to use the information above to calculate route-specific transportation risk. For illustration, we present a simple, manual calculation example below. Suppose that we have three track segments with different characteristics, including consequences such as the population in the evacuation zone (hypothetical and for illustration only):

- Segment 1: FRA track class 2, 10-mile-long, 1,000 people within the evacuation zone
- Segment 2: FRA track class 3, 15-mile-long, 500 people within the evacuation zone
- Segment 3: FRA track class 4, 20-mile-long, 250 people within the evacuation zone

We assume a train length of 100 cars, carrying 10 tank cars located at the train positions that are the most likely to derail. We also conservatively assume that the accident speed is the maximum track speed for each track class. Again, these assumptions are only made to illustrate the calculation process. The goal is to calculate the risk when one train transverses this three-segment-route for one shipment. Accident-cause-specific release probability information for this type of train is presented in Table 3(a) for broken rails, and Table 3(b) for track geometry defects.

For example, segment 1 is a Class 2 track. According to Table 3(a), the probability of release due to broken rails is estimated to be 20.22E-11 per train-mile. The segment is 10 miles long. For one train shipment, the release probability is 20.22E-10 (20.22E-11×10). The consequence is 1000 affected people. Therefore, the hazmat release risk per train shipment due to broken rails on this particular track segment is 20.22E-07 (20.22E-10×1000). Similarly, the risks on segments 2 and 3 can be estimated at 7.53E-07 and 1.97E-07, respectively. In total, the route-specific per train shipment due to broken rails is 29.72E-07. Similarly, using Table 3(b), the route risk due to track geometry defects on the same route is 2.86E-07 per train shipment.

In this example, hazmat release risk due to broken rails is seven times greater than the risk due to track geometry defects on this route. If 40 percent of broken rails on this route could be prevented, the release risk would be reduced proportionally, to 17.83E-07 (29.72E-07 – 29.72E-07 × 40%). This example demonstrates how the risk model can be used to understand the impact of accident cause prevention on hazmat transportation risk. This enables the assessment and comparison of different risk management strategies.

8 DISCUSSIONS

8.1 Unit Hazmat Train Risk Analysis

The methodology developed in this research can be used to quantify accident-cause-specific risk for unit trains as well. Our risk methodology firstly calculates train-position-specific derailment probability. Given a specific type of tank car at each position, we can further calculate its derailment and release probability. In terms of risk modeling, unit hazmat train is a special case where all train positions (excluding locomotives and buffer cars) contain hazardous materials. Note that this research only focuses on the releases caused by mechanical damage incurred by tank cars in train accidents, without accounting for releases resulting from thermal tearing, which is a process by which a fire impinging on the tank causes the steel to weaken. Accounting for thermal-tear-caused tank car release risk in unit-train operation requires a standalone study, and it is the next step of our research.

8.2 Research Contribution and Potential Implementation

This research develops a practical, generalized methodology to estimate accident-cause-specific hazmat transportation risk, accounting for track-related, train-related, and operational factors, for any train configuration. This research can be used to evaluate the potential impact of accident prevention on hazmat release risk, thereby aiding with the comparison and prioritization of alternative risk reduction strategies (e.g. broken rail prevention, track geometry quality improvement or tank car design improvement). Also, researchers can use the model to compare broken rail prevention versus tank car design enhancement in terms of the degree of risk reduction on a specific corridor or network. Given budget limitations, an optimal risk portfolio can be developed to allocate resources for alternative types of risk management strategies. Implementation of advanced risk models into practical use is pivotal for successful risk management. With this in mind, we are developing a prototype computer-aided decision support tool that can automate all the risk calculations described above. Using this tool, practitioners can easily change risk parameters, perform automated risk assessment in various "what-if" scenarios, and thus compare and implement promising risk mitigation approaches.

9 CONCLUSION

This paper develops a generalized risk analysis methodology that can estimate accident-cause-specific hazmat transportation risk, accounting for various train, track and operational characteristics, such as FRA track class, train length, speed, point of derailment, the number and placement of tank cars in a train, tank car safety design, and population density along rail lines. For illustration, the model is applied to estimate the risk due to broken rails and track geometry defects. The analysis shows that broken-rail-caused derailments tend to be associated with a higher release risk, due to its higher rate of occurrence and higher average severity (in terms of number of cars derailed). The risk analysis methodology has been implemented into a computer-aided decision support tool that automates risk calculations. The methods and tools developed herein can support the railroad industry in the quantitative risk management of hazardous materials transported by rail, particularly with respect to accident cause prevention.

10 FUTURE RESEARCH

Although this paper focused on the top two causes, the probabilistic risk analysis methodology can be applied to analyzing the risks due to other accident causes. Besides FRA track class, there could be other factors affecting derailment rates (*38*). For example, a curved track may have a different derailment rate compared to a tangent track, all else being equal (*39-41*). Future research is needed to collect safety and traffic information on this and other factors, thereby updating the safety statistics used in our methodology.

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AUTHOR CONTRIBUTION

The authors confirm contribution to the paper as follows: Study conception and design: Xiang Liu, Tejashree Turla, Zhipeng Zhang; Data collection, analysis and interpretation of results: Xiang Liu, Tejashree Turla, Zhipeng Zhang; Draft manuscript preparation: Xiang Liu, Tejashree Turla, Zhipeng Zhang. All authors reviewed the results and approved the final version of the manuscript.

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Figures

Tables

TABLE 1 Risk Management Strategies and Risk Factors

Risk Management Strategies	Risk Factors
• Train accident occurrence (*8*, *9*, *16*-*19*, *23*)	• Infrastructure condition • Equipment condition • Human factors • Traffic exposure, etc.
• Number of cars derailed (*25*, *26*)	• Speed • Accident cause • Point of derailment • Train length, etc.
• Number of hazmat cars derailed (*13*, *14*, *27*)	• Number of hazmat cars in the train • Train length • Placement of hazmat cars in the train, etc.
• Number of hazmat cars releasing contents (*10*, *11*, *12*, *23*)	• Accident speed • Hazardous materials car safety design, etc.
• Release consequences (*15*, *30*)	• Chemical property • Population density • Spill size • Environment, etc.

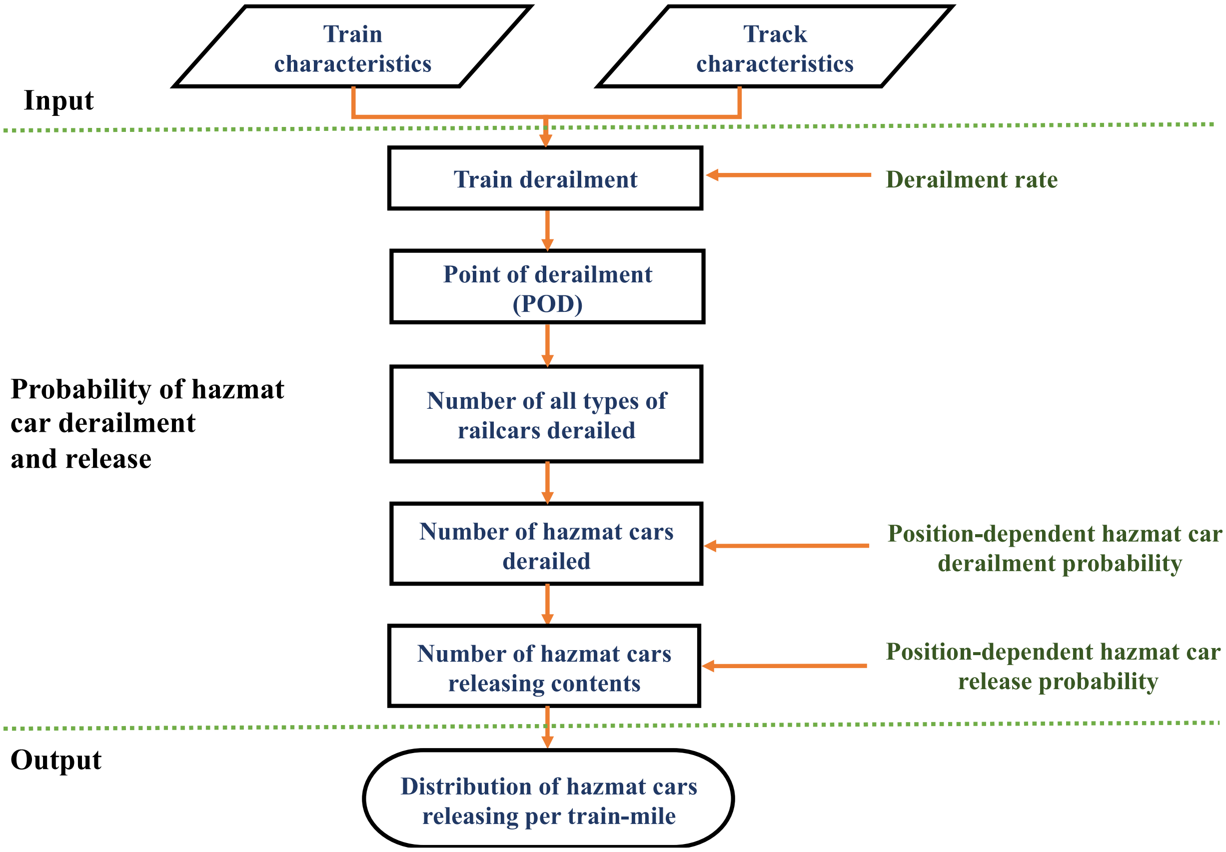


FIGURE 1 Accident-cause-specific hazmat release risk analysis framework.

TABLE 2 Class I Mainline Freight Train Derailments Due to Major Causes, 2000 to 2016

Cause Group	Description	All Types of Train Derailments	Hazmat Train Derailments	Total Number of Hazmat Cars Derailed
08T	Broken rails or welds	896	288	795
04T	Track geometry defects	444	193	223
10E	Bearing failure (car)	367	149	181
12E	Broken wheels (car)	332	85	164
09H	Train handling (excluding brakes)	288	136	112
01M	Obstructions	259	87	73
05T	Buckled track	236	70	210
03T	Wide gauge	234	63	152
04M	Track–train interaction	201	81	115
11E	Other axle or journal defects	190	34	37
	All causes (including the causes not listed in this table)	6,229	2,272	3,611

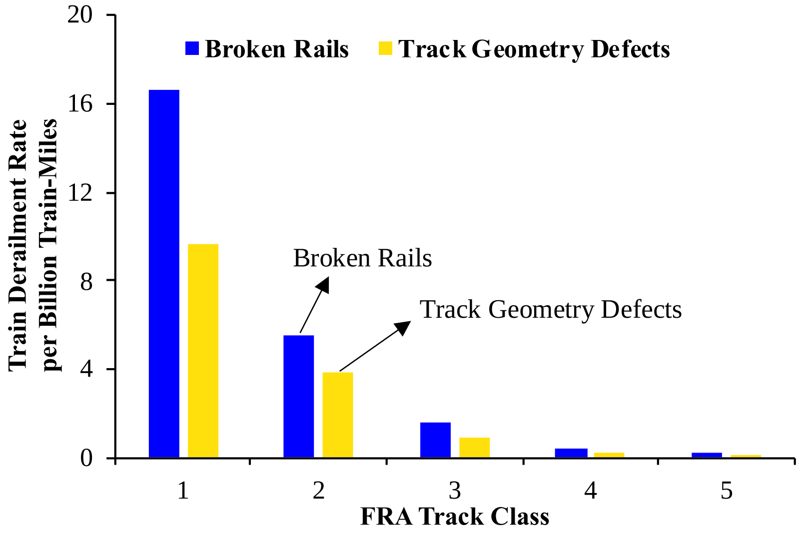


FIGURE 2 Accident-cause-specific train derailment rate by FRA track class.

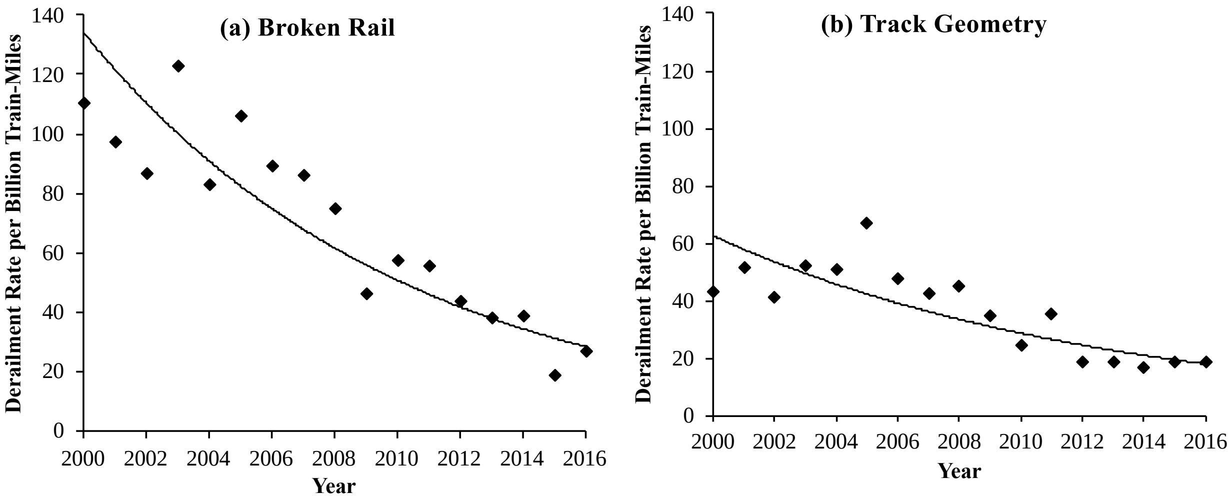


FIGURE 3 Class I mainline freight train derailment rate from 2000 to 2016.

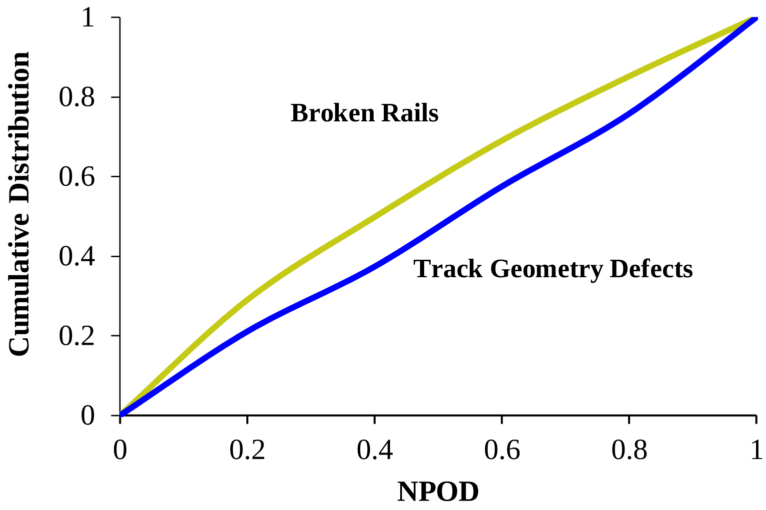


FIGURE 4 Fitted NPOD distributions by major accident causes.

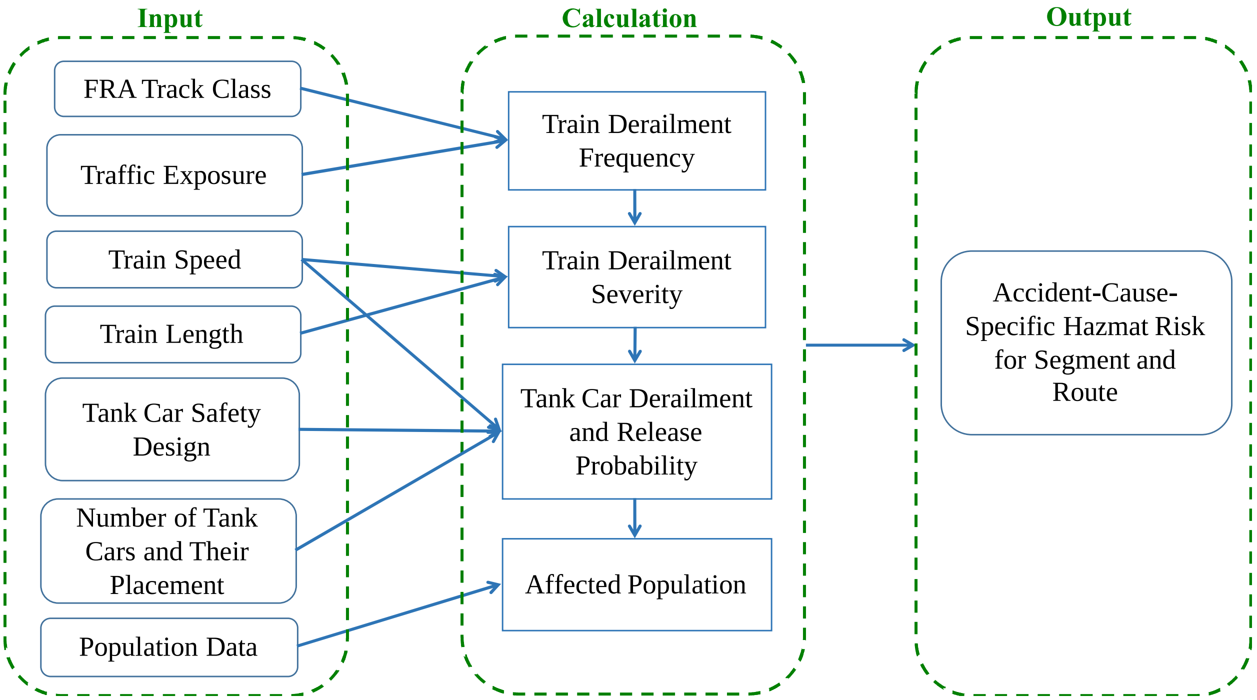
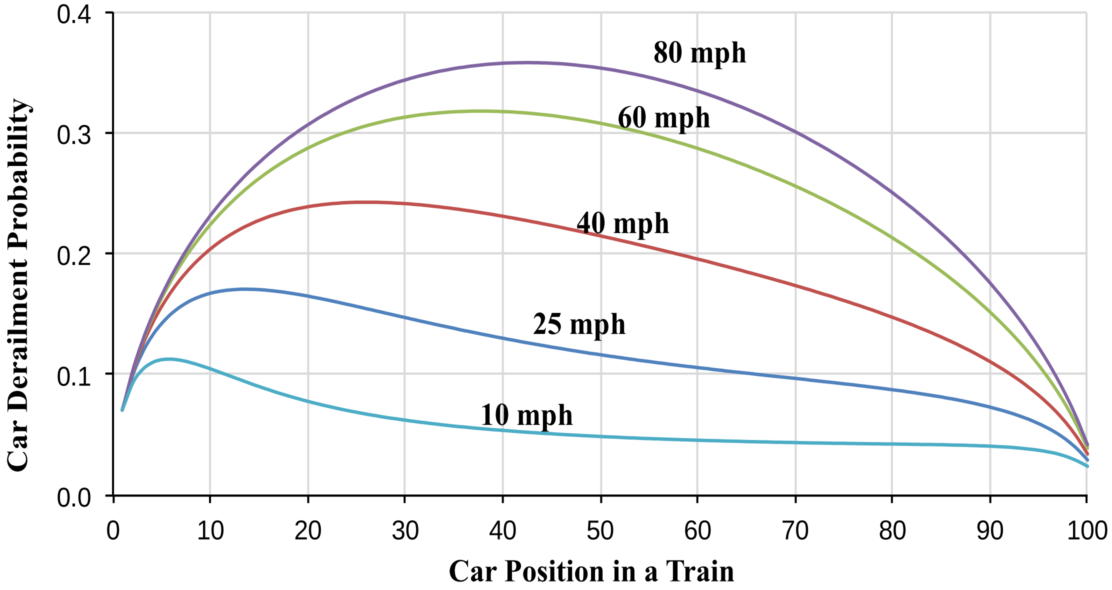
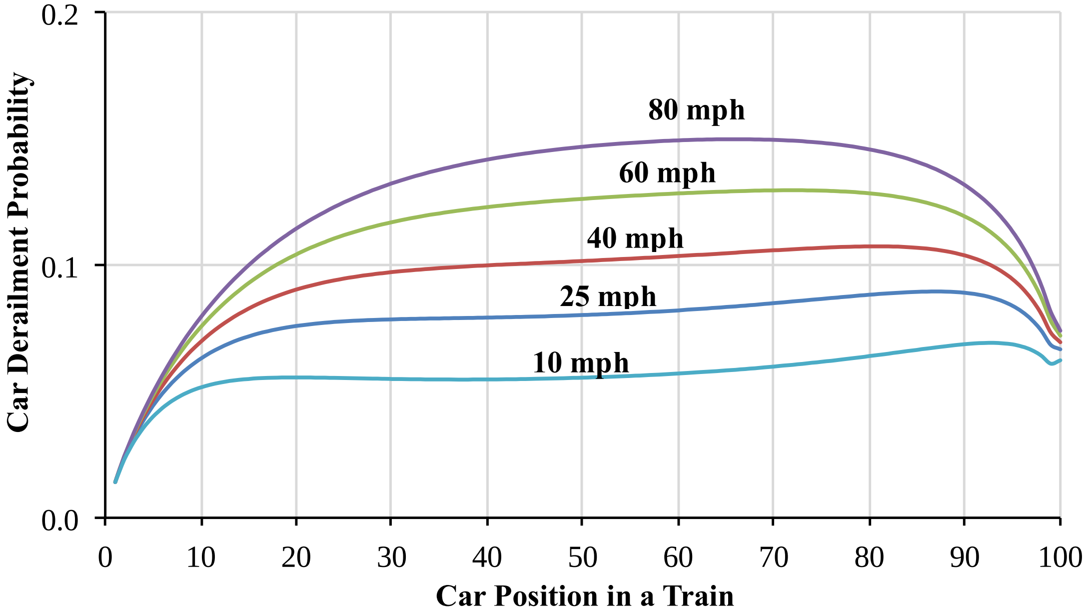


FIGURE 5 Implementation of decision support tool.



(a) Broken Rails



(b) Track Geometry Defects

FIGURE 6 Position-dependent car derailment by accident cause.

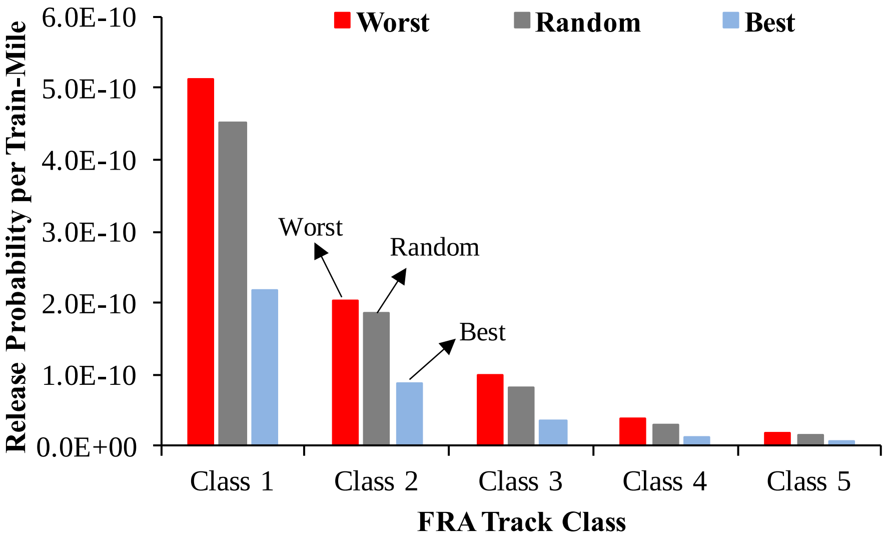
TABLE 3 Train Derailment and Release Probability by Accident Cause

(a) Broken Rails

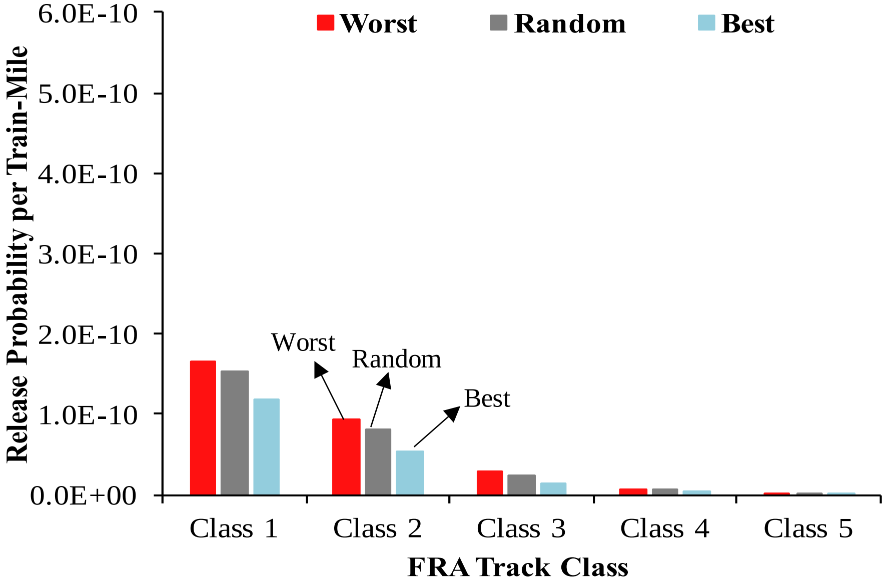
FRA Track Class	Train Derailment Rate per Train-Mile	Probability of At Least One Hazmat Car Release in a Train Derailment	Release Probability per Train-Mile
1	166.44E-10	0.03074	51.17E-11
2	55.32E-10	0.03656	20.22E-11
3	16.25E-10	0.06178	10.04E-11
4	4.73E-10	0.08345	3.95E-11
5	2.04E-10	0.09363	1.91E-11

(b) Track Geometric Defects

FRA Track Class	Train Derailment Rate per Train-Mile	Probability of At Least One Hazmat Car Release in a Train Derailment	Release Probability per Train-Mile
1	96.64E-10	0.01702	16.44E-11
2	38.72E-10	0.02396	9.28E-11
3	9.29E-10	0.02970	2.76E-11
4	2.04E-10	0.03613	0.74E-11
5	0.39E-10	0.04147	0.16E-11



(a) Broken Rails



(b) Track Geometry Defects

FIGURE 7 Hazmat release probability per train-mile by accident cause.