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Accident-Cause-Specific Risk Analysis of Rail Transport of Hazardous Materials

Xiang Liu[1], Tejashree Turla[1], and Zhipeng Zhang[1]

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 because of train accidents. The Federal Railroad Administration identifies over 300 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, this paper demonstrates 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.

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 release probability by tank car safety improvement; or 3) mitigation of release consequences. Prior research has largely focused on the latter two strategies, and 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 associated with 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.

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 (*4–12*). These studies have focused on various risk mitigation strategies, related to infrastructure (*4*, *7*), rolling stock (*13*), tank car safety enhancement (*13–16*), train makeup (*17*, *18*), or mitigation of release consequence (*19*). Each of these risk reduction strategies focuses on at least one event in the causal chain of an accident-caused release incident (Table 1).

Train Accident Occurrence

Many severe hazmat release incidents are caused by train accidents, particularly train derailments. Derailments account for over 72% of all types of accidents on freight railroads (*28*). The Federal Railroad Administration (FRA) of the U.S. Department of Transportation (U.S.

[1]Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, New Brunswick, NJ

Corresponding Author:
Address correspondence to Xiang Liu: xiang.liu@rutgers.edu

Table 1. Risk Management Strategies and Risk Factors

Risk management strategies	Risk factors
• Train accident occurrence (*7*, *13*, *20–24*)	• 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 (*17*, *18*, *27*)	• Number of hazmat cars in the train • Train length • Placement of hazmat cars in the train, etc.
• Number of hazmat cars releasing contents (*14–16*, *24*)	• Accident speed • Hazardous materials car safety design, etc.
• Release consequences (*10*, *19*)	• Chemical property • Population density • Spill size • Environment, etc.

DOT) identifies around 389 distinct accident causes (*29*) related to infrastructure, rolling stock, human factors, and other factors (*24*). Prior research found that over 70% of freight train mainline derailments were caused by either infrastructure defects or rolling stock failures (*24*). The hazmat risk reduction strategies include the prevention of track defects (*7*), equipment condition monitoring to reduce in-service failures (*30*), or the use of more advanced train control technologies to reduce human error (*31*).

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.

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*, *32*). Possible strategies for reducing the probability of tank car derailment include reducing the speed of the train to reduce the total number of vehicles derailed (*8*) and the placement of tank cars in the positions that are less likely to derail (*17*, *18*).

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 (*14–16*). In addition, reducing train speed can reduce the accident impact on the tank car, therefore decreasing release probability (*8*).

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. Geographical information systems (GIS) can be used for consequence analysis when integrated with other databases such as census and rail network data (*9*). 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 (*10*).

Knowledge Gaps

Although the prior research recognized the importance of evaluating hazmat transportation risk on the causal level, it 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.

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, it is possible to 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 AAR and RSI.

Methodology

The research methodology portrays the process of an accident-caused release incident. Each event in this process is subject to specified influencing factors. A probabilistic risk analysis (PRA) model is developed 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 caused by thermal tearing. The latter will be addressed through a separate study in the next step.

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:

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

where Y = number of train derailments, and M = traffic exposure.

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 (*6*, *33*). Equation 2 presents a probabilistic model to

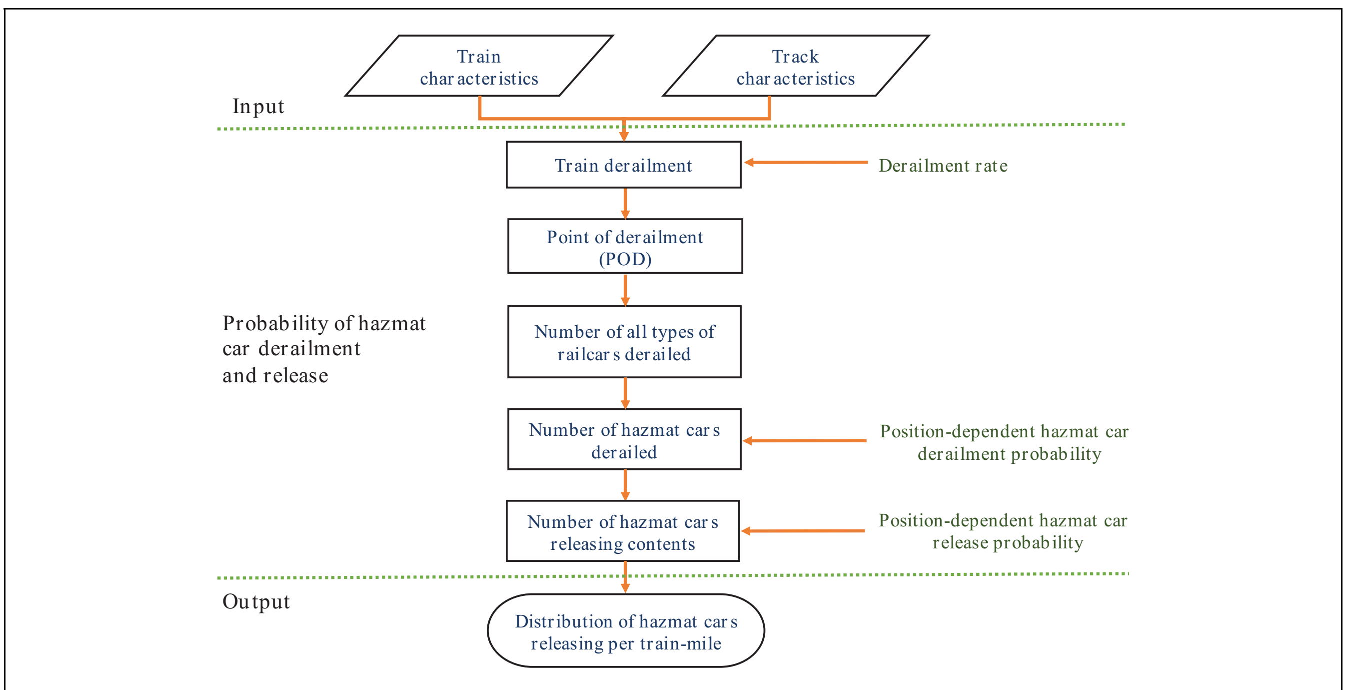

Figure 1. Accident-cause-specific hazmat release risk analysis framework.

estimate the derailment probability of a tank car at a given position of a train on a specific track segment.

$$\mathrm{PD}_i(j) = \sum_{k=1}^{j}\{\mathrm{POD}_i(k) \times \sum_{x=j-k+1}^{L-k+1} \mathrm{PN}_i(x)\} \quad (2)$$

where

$\mathrm{PD}_i(j)$ = probability of derailment for a vehicle at the j^{th} position of a train on the i^{th} segment,

$\mathrm{POD}_i(k)$ = point of derailment probability for the k^{th} position of a train on the i^{th} segment,

$\mathrm{PN}_i(x)$ = probability of derailing x vehicles in a train accident on the i^{th} segment, and

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

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 (*6*), denoted by $\mathrm{CPR}_i(j)$. Assuming that the releases of tank cars are independent, the probability that at least one hazmat tank car releases, denoted by $P_i(X_R|\mathrm{TD})$, is equal to one minus the total probability that none of the derailed tank cars release contents:

$$P_i(X_R|\mathrm{TD}) = \left\{1 - \prod_j [1 - \mathrm{PD}_i(j) \times \mathrm{CPR}_i(j)]\right\} \quad (3)$$

where

$P_i(X_R|\mathrm{TD})$ = probability of a release incident after a train is derailed on the i^{th} segment, and

$\mathrm{CPR}_i(j)$ = conditional probability of release (CPR) of a derailed tank car.

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.

$$R = \sum_{i=1}^{N} P_i C_i \quad (4)$$

where

R = hazardous material transportation risk (e.g., expected release consequence),

P_i = probability of a release incident on the i^{th} track segment,

C_i = consequence of a release (e.g., affected population) on the i^{th} segment, and

N = number of segments.

Segment-specific release probability (P_i) per train shipment can be estimated by

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

where

$P_i(\mathrm{TD})$ = probability of a train derailment when traversing the i^{th} segment,

$P_i(X_R|\mathrm{TD})$ = probability of a release incident after a hazmat train is derailed on the i^{th} segment,

Z_i = train derailment rate on the i^{th} segment, and

L_i = segment mileage.

Parameter Estimations in Risk Modeling

Freight Train Derailment Rate

This paper focuses on freight train derailments on Class I railroad mainlines, excluding other types of accidents (e.g., collisions 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. The top two causes are used as

Table 2. Major Causes of Class I Mainline Freight Train Derailments, 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

examples because they collectively account for around 20% of all freight train derailments on Class I mainlines (*24*). However, the generic PRA methodology developed here can be adapted to other causes as well.

The train derailment rate is affected by several factors, such as FRA track class, method of operation, and annual traffic density (*11*). This analysis focuses on FRA track class, which has been identified as a key influencing factor (*11*, *25*, *34*, *35*). 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. This study does not further delineate accident statistics according to additional factors; this is to avoid a small sample size that will cause statistical sampling biases (*6*). 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. Moreover, 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 the study's risk model.

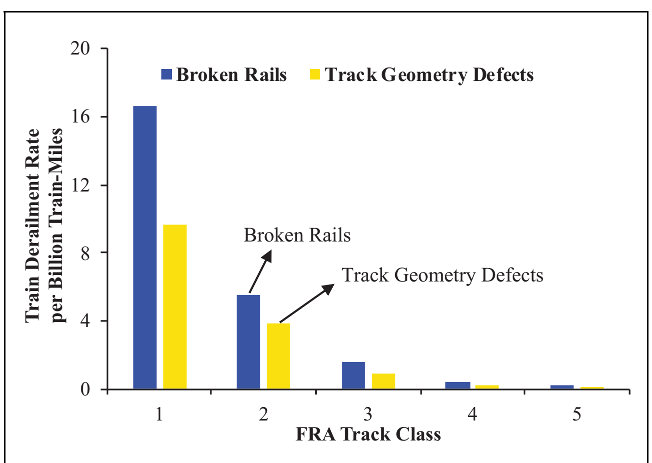

Figure 2. Accident-cause-specific train derailment rate by FRA track class.

For the Class 1 mainline freight train derailment rate from 2000 to 2016, the average annual decline rates were 10.6% and 8.7% for 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 (*36*). In this study, let the reference year be 2008, as its derailment rate is closest to the 17-year average. Other analysts can also use this approach to update derailment rate statistics using future data.

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.

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

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

For train derailment severity analysis, the response variable is the total number of cars derailed per accident. A truncated geometric (TG) regression model was developed to account for derailment speed, residual train length (RL $= L - \mathrm{POD} + 1$), 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 defects (Equations 8, 9). The modeling details can be found in (*25*, *26*).

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

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

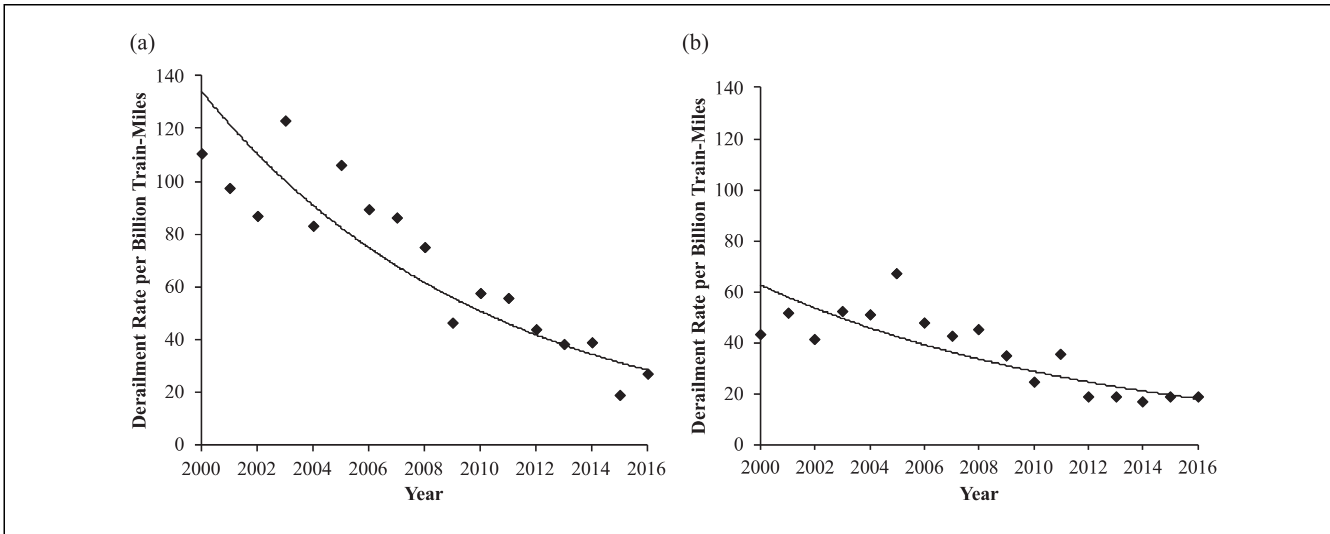

Figure 3. Class I mainline freight train derailment rates from 2000 to 2016 for (*a*) broken rails and (*b*) track geometry defects.

where

DS = logarithmic derailment speed (the speed is in mph),

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

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).

Point of Derailment

The normalized point of derailment (NPOD) is a metric accounting for train length heterogeneity. It is equal 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 k^{th} position, POD(k), can be estimated using

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

where

POD(k) = POD probability at the k^{th} position of a train,

$F()$ = cumulative density distribution of the fitted NPOD distribution, and

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 (*6*).

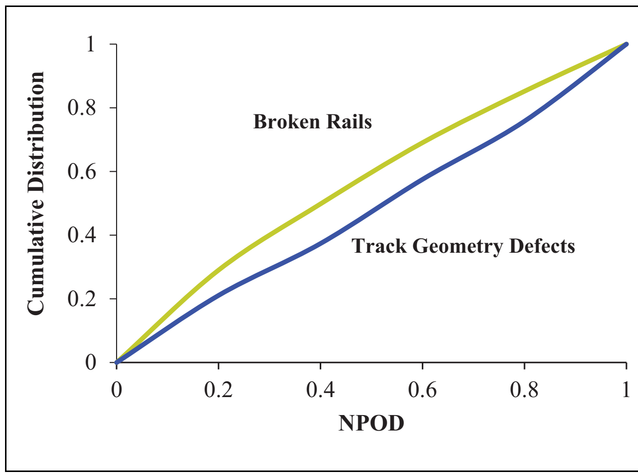

Figure 4. Fitted NPOD distributions by major accident causes.

Decision Support Tool

As part of this research, an automatic risk decision support tool is being developed (Figure 5). This tool consists of built-in formulas (presented above) 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, and so forth). A numerical example will be provided below to demonstrate the practical use of the tool for route-specific risk assessment.

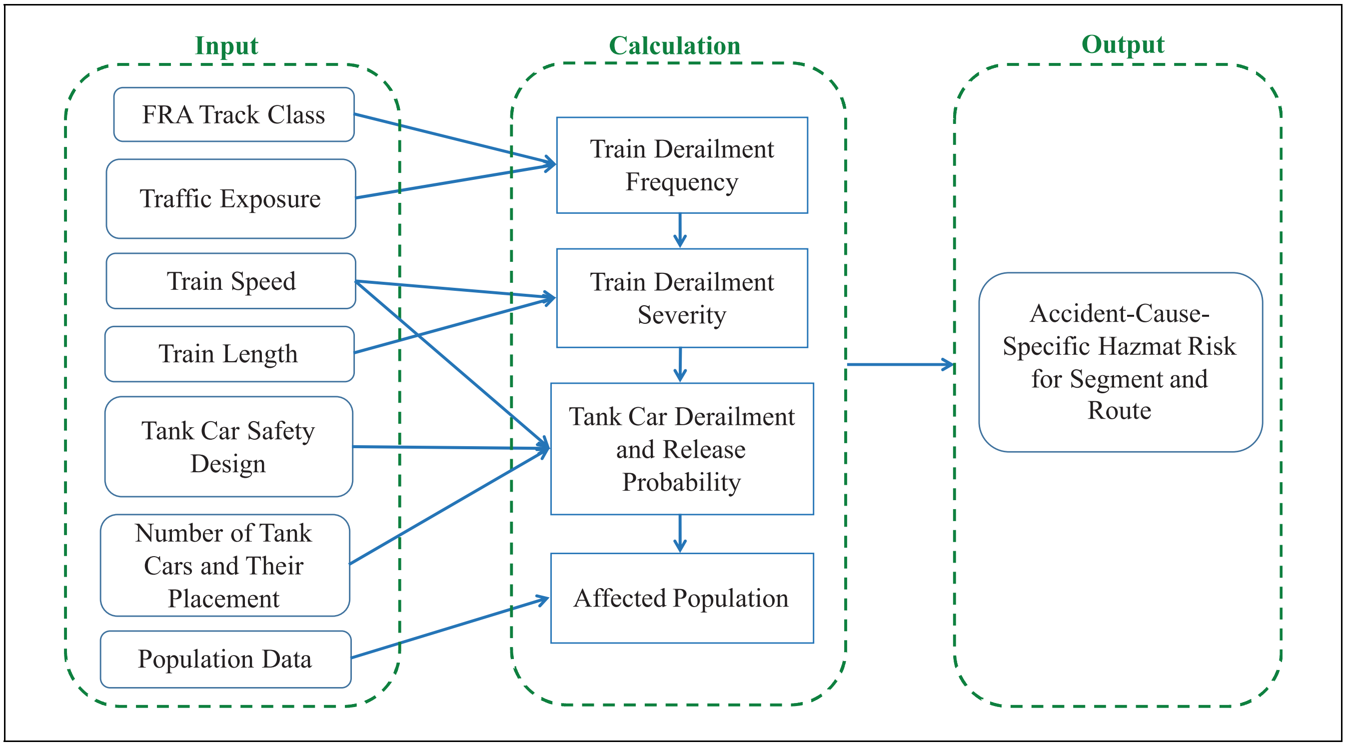

Figure 5. Implementation of decision support tool.

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.

Numerical Example

Position-Dependent Derailment Probability

In this section, a numerical example is presented to explain the practical use of the methodology described above. For illustrative convenience, the paper focuses on broken rails and track geometry defects. The methodology can be adapted to other causes. In this paper, 100 vehicles per train are assumed, 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 this 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.

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, because of 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, it can be seen 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 (*20*, *23*).

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 (*36*). It is also conservatively assumed 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, in which 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.

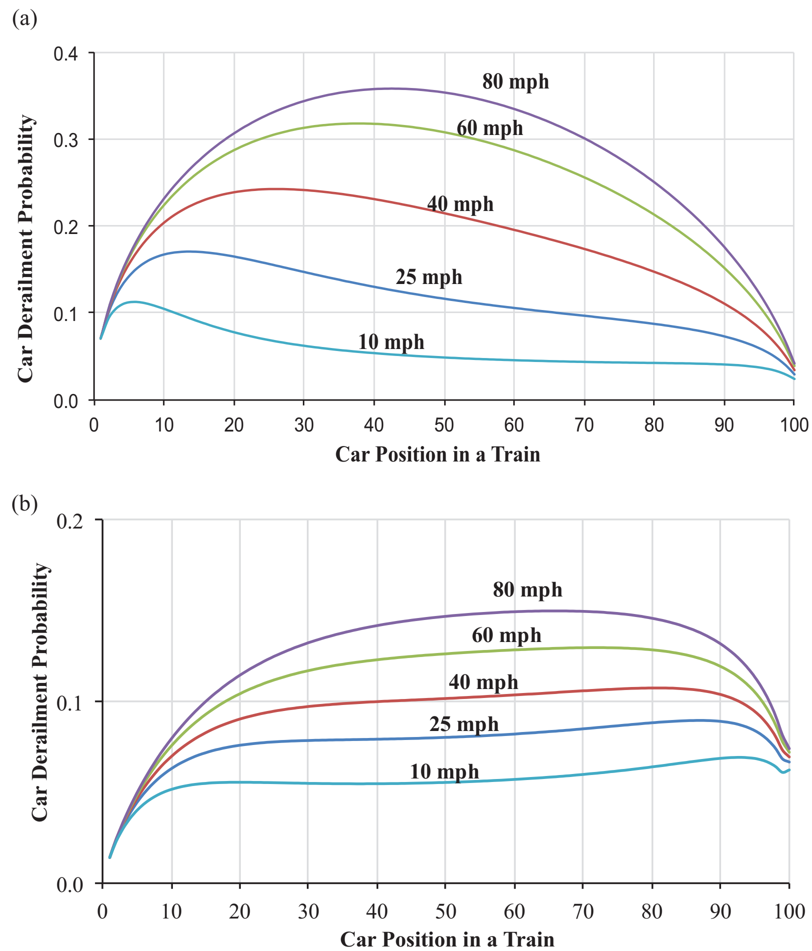

Figure 6. Position-dependent car derailment by accident cause for (*a*) broken rails and (*b*) track geometry defects.

Table 3. Train Derailment and Release Probability by Accident Cause

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
Broken rails			
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
Track geometric defects			
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

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 perhaps increasing the probability of tank car derailment and release (*36*). 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 that on Track Class 4, and six times the release probability on Track Class 5.

Effect of Tank Car Positions

Previous studies have suggested that the tank car derailment probability is affected by the car's position in the train. Therefore, change of tank car position was identified as a potential risk reduction strategy (*37*). In the example above, the worst case scenario was considered. In this subsection, a severity analysis is presented 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 placements. On the same track class, release probability per train-mile varies by tank car position (Figure 7).

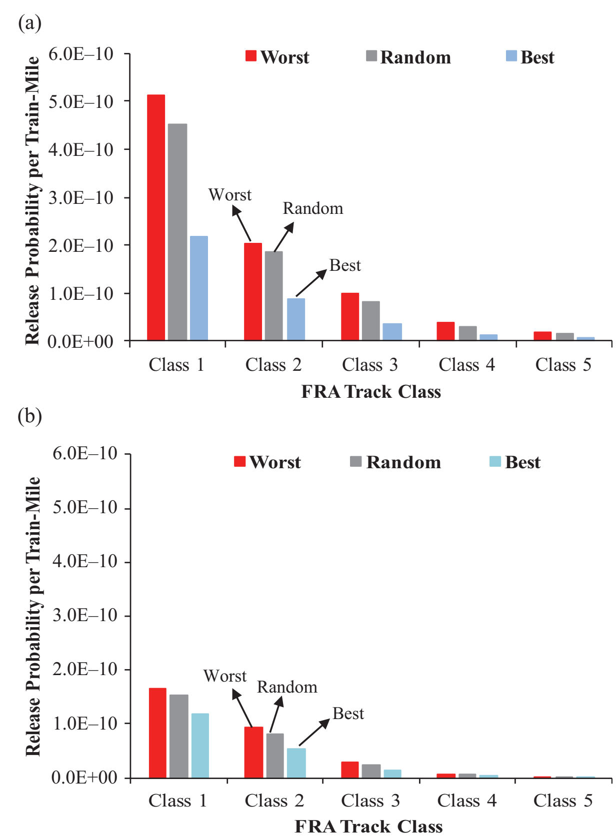

Figure 7. Hazmat release probability per train-mile by accident cause for (*a*) broken rails and (*b*) track geometry defects.

Route Transportation Risk Calculation

This section discusses how to use the information above to calculate route-specific transportation risk. For illustration, a simple, manual calculation example is presented below. Suppose that there are 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 mi long, 1,000 people within the evacuation zone;
- Segment 2: FRA Track Class 3, 15 mi long, 500 people within the evacuation zone;
- Segment 3: FRA Track Class 4, 20 mi long, 250 people within the evacuation zone.

Let it be assumed that there is a train length of 100 cars, carrying 10 tank cars located at the train positions that are the most likely to derail. It is also conservatively assumed 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 traverses this three-segment route for one shipment. Accident-cause-specific release probability information for this type of train is presented in Table 3 for broken rails and for track geometry defects.

For example, Segment 1 is a Class 2 track. According to Table 3, the probability of release because of broken rails is estimated to be 20.22E−11 per train-mile. The segment is 10 mi long. For one train shipment, the release probability is 20.22E−10 (20.22E−11 × 10). The consequence is 1,000 affected people. Therefore, the hazmat release risk per train shipment because of broken rails on this particular track segment is 20.22E−07 (20.22E−10 × 1,000). 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 risk per train shipment because of broken rails is 29.72E−07. Similarly, using Table 3, the route risk because of track geometry defects on the same route is 2.86E−07 per train shipment.

In this example, hazmat release risk because of broken rails is 10 times greater than the risk because of track geometry defects on this route. If 40% 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.

Discussions

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. The risk methodology first calculates train-position-specific derailment probability. Given a specific type of tank car at each position, the method can further calculate its derailment and release probability. For risk modeling, a unit hazmat train is a special case in which 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 the research.

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). Moreover, 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, the authors 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.

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 created by broken rails and track geometry defects. The analysis shows that broken-rail-caused derailments tend to be associated with a higher release risk, because of their 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 here can support the railroad industry in the quantitative risk management of hazardous materials transported by rail, particularly with respect to accident cause prevention.

Future Research

Although this paper focused on the top two causes, the PRA methodology can be applied to analyzing the risks generated by 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 with 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 the methodology.

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Author Contributions

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.

References

1. Ling, L., M. Dhanasekar, and D. P. Thambiratnam. A Passive Road-Rail Crossing Design to Minimize Wheel-Rail Contact Failure Risk Under Frontal Collision of Trains onto Stuck Trucks. *Engineering Failure Analysis*, Vol. 80, 2017, pp. 403–415.
2. Britton, M.A., G. J. M. Read, and S. Asnaashari. Analysis of Train Derailment Cause and Outcome in Victoria, Australia, between 2007 and 2013: Implications for Regulation. *Journal of Transportation Safety & Security*, Vol. 9, No. 1, 2017, pp. 45–63.
3. Liu, X. Statistical Causal Analysis of Freight-Train Derailments in the United States. *Journal of Transportation. Part A: Systems*, Vol. 143, No. 2, 2017, p04016007.
4. Liu, X., M. R. Saat, and C. P. L. Barkan. Integrated Risk Reduction Framework to Improve Railway Hazardous Materials Transportation Safety. *Journal of Hazardous Materials*, Vol. 260, 2013, pp. 131–140.
5. Liu, X. Risk Comparison of Transporting Hazardous Materials in Unit Trains Versus Mixed Trains. *Transportation Research Record: Journal of the Transportation Research Board*, 2017. 2608: 134–142.
6. Liu, X., M. R. Saat, and C. P. L. Barkan. Probability Analysis of Multiple-Tank-Car Release Incidents in Railway Hazardous Materials Transportation. *Journal of Hazardous Materials*, Vol. 276, 2014, pp. 442–451.
7. Liu, X., M. R. Saat, and C. P. L. Barkan. Safety Effectiveness of Integrated Risk Reduction Strategies for Rail Transport of Hazardous Materials. *Transportation Research Record: Journal of the Transportation Research Board*, 2013. 2374: 102–110.
8. Kawprasert, A., and C. P. L. Barkan. Effect of Train Speed on Risk Analysis of Transporting Hazardous Materials by Rail. *Transportation Research Record: Journal of the Transportation Research Board*, 2010. 2159: 59–68.
9. Verma, M., and V. Verter. Railroad Transportation of Dangerous Goods: Population Exposure to Airborne Toxins. *Computers & Operations Research*, Vol. 34, No. 5, 2007, pp. 1287–1303.
10. Branscomb, L., M. Fagan, P. E. Auerswald, R. N. Ellis, and R. Barcham. *Rail Transportation of Toxic Inhalation Hazards: Policy Responses to the Safety and Security Externality*. RPP-2010-01. J.F.K. School of Government, Harvard University, 2010.
11. Liu, X., M. R. Saat, and C. P. L. Barkan. Freight-Train Derailment Rates for Railroad Safety and Risk Analysis. *Accident Analysis and Prevention*, Vol. 98, 2017, pp. 1–9.
12. Nayak, P. R., D. B. Rosenfield, and J. H. Hagopian. *Event Probabilities and Impact Zones for Hazardous Materials Accidents on Railroads*. Report DOT/FRA/ORD-83/20, FRA. U.S. Department of Transportation, Washington D.C., 1983.
13. Schlake, B. W., C. P. L. Barkan, and J. Edwards. Train Delay and Economic Impact of In-Service Failures of Railroad Rolling Stock. *Transportation Research Record: Journal of the Transportation Research Board*, 2011. 2261: 124–133.
14. Barkan, C. P. L. Improving the Design of Higher-Capacity Railway Tank Cars for Hazardous Materials Transport: Optimizing the Trade-Off Between Weight and Safety. *Journal of Hazardous Materials*, Vol. 160, No. 1, 2008, pp. 122–134.
15. Saat, M. R., and C. P. L. Barkan. Generalized Railway Tank Car Safety Design Optimization for Hazardous Materials Transport: Addressing the Trade-Off between Transportation Efficiency and Safety. *Journal of Hazardous Materials*, Vol. 189, No. 1, 2011, pp. 62–68.
16. United States Department of Transportation. *Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High Hazard Flammable Trains*. PHMSA-0082 (HM-251). Washington, D.C., 2012.
17. Bagheri, M., F. F. Saccomanno, S. Chenouri, and L. P. Fu. Modelling Hazardous Materials Risks for Different Train Make-Up Plans. *Transportation Research Part E: Logistics and Transportation Review*, Vol. 48, No.5, 2012, pp. 907–918.
18. Bagheri, M., M. Verma, and V. Verter. Transport Mode Selection for Toxic Gases: Rail or Road? *Risk Analysis*, Vol. 34, No. 1, 2014, pp. 168–186.
19. Yoon, H., C. J. Werth, C. P. L. Barkan, D. J. Schaeffer, and P. Anand. An Environmental Screening Model to Assess the Consequences to Soil and Groundwater from Railroad-Tank-Car Spills of Light Non-Aqueous Phase Liquids. *Journal of Hazardous Materials*, Vol. 165, No.1, 2009, pp. 332–344.
20. National Transportation Safety Board. *Railroad Accident Brief BNSF Railway Unit Ethanol Train Derailment*. Lesterville, South Dakota, 2017.
21. National Transportation Safety Board. *Railroad Accident Brief CSXT Petroleum Crude Oil Train Derailment and Hazardous Materials Release*, 2017.
22. Federal Railroad Administration. *Safe Placement of Train Cars: A Report*. U. S. Department of Transportation, Federal Railroad Administration, Washington, D.C., 2005.
23. Federal Railroad Administration. *Risk Evaluation Framework and Selected Metrics for Tank Cars Carrying Hazardous Materials*. Federal Railroad Administration, Washington, D.C., 2015.
24. Liu, X., M. R. Saat, and C. P. L. Barkan. Analysis of Causes of Major Train Derailment and Their Effect on Accident Rates. *Transportation Research Record: Journal of the Transportation Research Board*, 2012. 2289: 154–163.
25. Saccomonno, F. F., and S. M. El-Hage. Establishing Derailment Profile by Railcars Carrying Dangerous Commodities through Effective Marshalling Strategies. *Transportation Research Record: Journal of the Transportation Research Board*, 1989. 1245: 34–51.
26. Saccomonno, F. F., and S. M. El-Hage. Establishing Derailment Profile by Position of Corridor Shipments of Dangerous Goods. *Canadian Journal Civil Engineering*, Vol. 18, No. 1, 1991, pp. 67–75.
27. Glickman, T. S., E. Erkut, and M. S. Zschohke. The Cost and Risk Impacts of Rerouting Railroad Shipments of Hazardous Materials, *Accident Analysis Prevention*, Vol. 39, No. 5, 2007, pp. 1015–1025.
28. Liu, X. Collision Risk Analysis of Freight Trains in the United States. *Transportation Research Record: Journal of the Transportation Research Board*, 2016. 2546: 121–128.

29. Federal Railroad Administration. *Railroad Safety Statistics - Preliminary Annual Report*. U.S. Department of Transportation, 2011.
30. Federal Railroad Administration. *Office of Safety Analysis 3.01 − Accident Trends – Summary Statistics*. Federal Railroad Administration, 2015.
31. Martland, C., Y. Zhu, Y. Lahrech, and J. Sussman. Risk and Train Control: A Framework for Analysis. *Transportation Research Record: Journal of the Transportation Research Board*, 2001. 1742: 25–33.
32. Liu, X., M. R. Saat, X. Qin, and C. P. L. Barkan. Analysis of U.S. Freight-Train Derailment Severity Using Zero-Truncated Negative Binomial Regression and Quantile Regression. *Accident Analysis and Prevention*, Vol. 59, 2013, pp. 87–93.
33. Liu, X. Optimizing Rail Defect Inspection Frequency to Reduce the Risk of Hazardous Materials Transportation by Rail. *Journal of Loss Prevention in the Process Industries*, Vol. 48, 2017, pp. 151–161.
34. Liu, X., M. R. Saat, and C. P. L. Barkan. Analysis of Derailments by Accident Cause: Evaluating Railroad Track Upgrades to Reduce Transportation Risk. *Transportation Research Record: Journal of the Transportation Research Board*, 2011. 2261: 178–185.
35. Liu, X., and B. Schlake. Derailment Risk Analysis of Liquefied Natural Gas (LNG) Tenders on Mainline Freight Trains in the United States. *Transportation Research Part C –Emerging Technologies*, Vol. 72, 2016, pp. 77–92.
36. Liu, X. Risk Analysis of Transportation Crude Oil by Rail: Methodology and Decision Support System. *Transportation Research Record - Journal of the Transportation Research Record*, 2016. 2547: 57–65.
37. Bagheri, M., F. F. Saccomanno, S. Chenouri, and L. P. Fu. Reducing the Threat of In-Transit Derailments Involving Dangerous Goods through Effective Placement along the Train Consist. *Accident Analysis Prevention*, Vol. 43, No. 3, 2011, pp. 613–620.
38. Liu, X. Statistical Temporal Analysis of Freight-Train Derailment Rates in the United States: 2000 to 2012. *Transportation Research Record: Journal of the Transportation Research Board*, 2015. 2476: 119–125.
39. Xiao, X., X. Jin, Y. Deng, and Z. Zhou. Effect of Curved Track Support Failure on Vehicle Derailment. *International Journal of Vehicle Mechanics and Mobility*, Vol. 46, No. 11, 2008, pp. 1029–1059.
40. Silvia, M. I., I. R. Julia, H. César, and M. Laura. Derailment Risk and Dynamics of Railway Vehicles in Curved Tracks: Analysis of the Effect of Failed Fasteners. *Journal of Modern Transportation*, Vol. 24, No. 1, 2016, pp. 38–47.
41. Xiao, X., X. Jin, Z. Wen, M. Zhu, and W. Zhang. Effect of Tangent Track Buckle on Vehicle Derailment. *Multibody System Dynamics*, Vol. 25, No. 1, 2011, pp. 1–41.

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