Risk Comparison of Transporting Hazardous Materials in Unit Trains Versus Mixed Trains

Xiang Liu

This research developed an integrated, generalized risk analysis methodology for comparing hazardous materials transportation risk in unit trains versus mixed trains for the same amount of traffic demand. The risk methodology accounted for FRA track class, method of operation, annual traffic density, train length, speed, point of derailment, the number and placement of tank cars in a train, tank car placement, tank car safety design, and population density along the rail line. With these inputs, the methodology estimates train derailment rate, the probability of tank car derailment and release, and release consequence by train configuration. The analysis showed that tank car positions could affect the risk comparison between unit trains and mixed trains in transporting hazardous materials. In particular, if all tank cars were in positions that were least prone to derailment, distributing tank cars to many unit trains could reduce the overall risk. Otherwise, consolidating tank cars into unit trains could lead to a lower risk. The methodology has been implemented in a computer-aided decision support tool that automatically calculates the risk values for various track, rolling stock, and operational characteristics.

More than 2 million tank-car loads of hazardous materials (hazmat) are transported annually by rail in the United States. Recently, the boom in production of petroleum crude oil and natural gases from shale has dramatically increased the rail transport volume of flammable energy resources. In 2015, U.S. Class I railroads (BNSF Railway, Canadian National Railway, Canadian Pacific Railway, CSX Transportation, Kansas City Southern Railway, Norfolk Southern Railway, and Union Pacific Railroad) originated about 412,000 carloads of crude oil (*1*).

Unlike roadway transport by a single tank trailer, a train can carry many hazmat cars. Railroads extensively use unit trains (which may contain 50 to 120 loaded hazardous materials cars) to ship crude oil, sometimes hauling approximately 3 million gal of crude oil per train (*2*). In addition to unit trains, a train may contain a mix of both hazardous-materials cars and nonhazardous-materials cars. In general, the use of unit trains is determined by shippers according to the loading capability at the origin facility.

Various train configurations can be used to transport hazardous materials, and they have their comparative risks. For example, a unit train carries 100 tank cars. If these 100 cars are placed in 100 mixed trains, each of which has only one tank car, would the 100 mixed trains have a different risk than one unit train that has 100 tank cars of the same type? On one hand, consolidating many tank cars into one train would reduce the number of hazmat train shipments, reducing hazmat train derailment frequency. On the other hand, doing so would likely increase the probability of a release incident if many tank cars are involved in the derailment.

To the author's knowledge, little previous research explicitly modeled and compared hazardous-materials transportation risk in unit trains versus mixed trains for transporting the same number of hazmat cars. This knowledge gap motivated the development of the research in this paper. The research developed a generalized risk analysis model that is adaptable to any train configuration. A particular application of the methodology is toward understanding to what degree placing hazmat cars in one unit train would affect the transportation risk of that train, compared with placing these tank cars in multiple mixed trains.

This paper is structured as follows. First, relevant previous studies are reviewed, and knowledge gaps and potential solutions are identified. Second, a generalized, flexible risk analysis methodology is introduced that can estimate hazardous material transportation risk, accounting for any track infrastructure characteristic and train configuration. Third, a computer-aided risk calculator is presented that can automatically generate various risk profiles according to user-defined track and train characteristics. Fourth, the use of the methodology and a decision support tool are illustrated through numerical examples. Finally, the paper concludes with major findings and suggests possible future research directions.

LITERATURE REVIEW

Railroad hazardous materials risk management has received growing interest from academia and the transportation industry. Previous research has focused on aspects of risk management such as infrastructure (*3, 4*), rolling stock (*5*), tank car safety enhancement (*6–8*), train makeup (*9, 10*), and mitigation of release consequence (*11*). These studies synthetically structured railroad hazardous materials transportation as a multievent, multifactor risk management problem. Figure 1 shows that a release incident is the result of a five-step process: (*a*) train derailment, (*b*) number of cars derailed, (*c*) number of hazardous materials cars derailed, (*d*) number of hazmat cars releasing, and (*e*) release consequences.

Several risk reduction strategies have been developed or are under consideration. These strategies are categorized as follows:

1. Train accident prevention. A train accident is the initiating event of an accident-caused railroad hazmat release incident (non-

Department of Civil and Environmental Engineering, School of Engineering, Rutgers University, 96 Frelinghuysen Road, Piscataway Township, NJ 08854. xiang.liu@rutgers.edu.

Transportation Research Record: Journal of the Transportation Research Board, No. 2608, 2017, pp. 134–142.
http://dx.doi.org/10.3141/2608-15

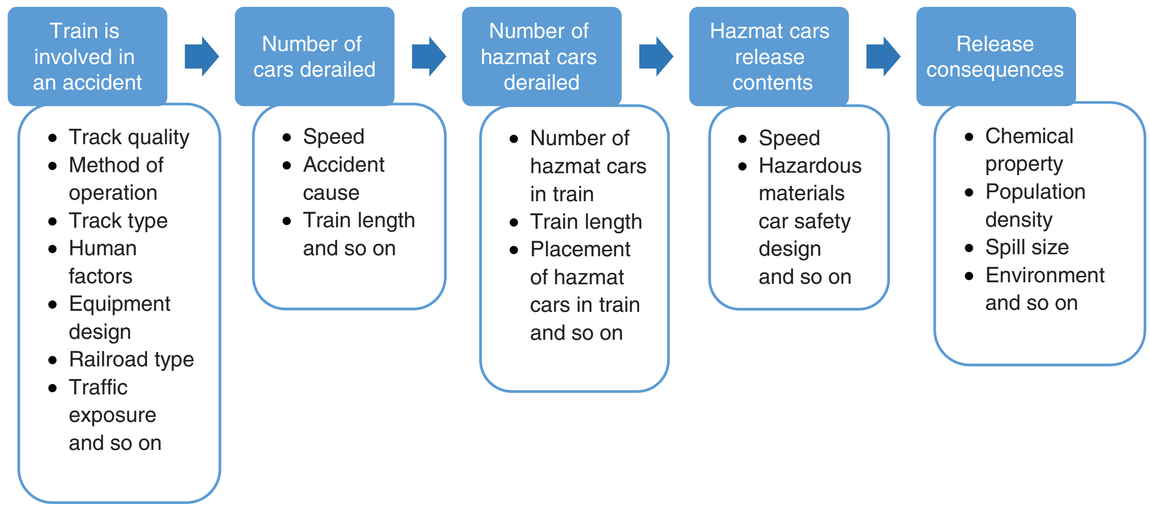

FIGURE 1 Event chain of railroad hazardous materials release incident (*12*).

accident-caused release is beyond the scope of this paper). The FRA Rail Equipment Accident database records more than 400 distinct accident causes (*13*). An analysis of historical train accident data found that derailments accounted for 72% of all types of accidents on main lines (*14*), and more than 70% of derailments were caused by infrastructure or rolling stock failures (*15*). Therefore, promising hazmat risk reduction strategies include the prevention of track defects (*3, 4, 16*), equipment condition monitoring to reduce in-service failures (*5*), and use of advanced train control technologies to reduce human error (*17*).

2. Reduction of the probability of tank car derailment. After a train accident occurs, reducing the probability of tank car derailment can also mitigate the risk. Possible strategies include train speed reduction to reduce the total number of vehicles derailed (*18*) and placing tank cars in positions that are less likely to derail (*9, 10*).

3. Reduction of tank car release probability. Studies have found that the use of a more robust tank car design can reduce tank car release probability, reducing hazmat transportation risk (*6–8*). In addition, reducing train speed can mitigate the accident impact on the tank car, decreasing the probability of release (*18*).

4. Reduction of hazmat release consequence. The consequences of a release can be measured with various metrics, such as property damage, environmental impact, traffic delay, or affected population. The use of a lower-hazard chemical or rerouting of hazmat traffic to avoid populated areas have been identified as potential strategies to mitigate hazmat transportation risk (*19*).

KNOWLEDGE GAPS

Although most previous studies focused on accident prevention and severity mitigation for a given train configuration, little previous work compared the risks with the use of different types of trains, particularly unit trains versus multiple mixed trains for the same traffic demand. As the Great Lakes Commission stated, “mixed trains carrying crude oil are not adequately studied in risk analysis and emergency preparedness programs that address crude oil transport” (*20*). This paper narrows the knowledge gap by developing an integrated, generalized risk analysis methodology, accompanied by a decision support tool, to automatically estimate hazmat transportation risk for unit trains versus mixed trains. Although the methodology is particularly relevant to flammable liquid, which predominantly travels by unit train, it is adaptable to all types of hazardous materials transported by various types of hazmat trains.

RESEARCH OBJECTIVE AND SCOPE

This research contributes to the literature and practice in the following aspects:

1. Development of a probabilistic risk analysis (PRA) model that will quantify the likelihood and consequence of a hazmat release incident, accounting for any train configuration.
2. Implementation of the risk analysis methodology in a computer-aided decision support tool that automates risk calculation and comparison.
3. Use of the decision support tool to generate various risk profiles given different hazmat train configurations.

Accomplishing these objectives would advance both the state of the art and the state of practice in hazmat transportation risk analysis, allowing the railroad industry to draw new managerial insights with respect to the optimal train configuration and placement of tank cars to mitigate transportation risk. This research focuses on the transportation risk on main lines. The hazmat release risk in yards is beyond of the scope of this paper. Also, this research centered on the risk aspect of train configuration, without accounting for all practical engineering and cost implications pertinent to train makeup. Furthermore, this research did not account for multiple-tank-car releases related to thermal tearing in a fire initiated by a flammable liquid release. This type of tank car release requires a different modeling process.

METHODOLOGY

Risk is the combination of the probability and the consequence (*21*). For one train shipment, if a release occurs on the second segment, it indicates that there is no release on the first segment. So, the probability of release is $(1 - P_1)P_2$, where P_1 and P_2 represent train derailment probability on the first segment and the second segment, respectively. The consequence of release on the second segment is C_2. Therefore, in this case, the expected consequence (risk) is $(1 - P_1)P_2C_2$. Similarly, if a release occurs on the ith segment, it means that there is no release incident on any of the previous segments $(1, 2, 3, \ldots, i - 1)$. This study assumed that a train shipment will terminate if a derailment occurs. With these considerations and assumptions, route-specific railroad hazmat transportation risk per train shipment is calculated as follows:

$$R = P_1C_1 + (1 - P_1)P_2C_2 + \cdots + \prod_{j=1}^{i-1}(1 - P_j)P_iC_i \quad (1)$$

where

R = accident-caused hazardous materials transportation risk,
P_i = probability of a release incident on the ith segment, and
C_i = consequence of a release (e.g., affected population) on the ith segment.

In Equation 1, segment-specific release probability is sufficiently small (on the order of 10^{-6} per shipment); thus

$$\prod_{j=1}^{i-1}(1 - P_j) \approx 1 \quad (2)$$

Based on this approximation, Equation 1 can be simplified as follows:

$$R \approx \sum_{i=1}^{N} P_iC_i \quad (3)$$

Segment-specific release probability (P_i) is further estimated as a product of train accident probability (P_i(TD)) and the conditional probability that a train accident causes a release ($P_i(X_R|\text{TD})$):

$$P_i = P_i(TD) \times P_i(X_R|TD) \quad (4)$$

where P_i(TD) is the probability of a hazmat train accident when this train traverses the ith track segment and $P_i(X_R|\text{TD})$ is the probability of a release incident after a hazmat train accident occurs.

The train accident rate (Z_i) is sufficiently small; therefore, according to these conditions, accident probability on a segment is approximately equal to the product of accident rate and segment length (*3, 4*):

$$P_i(TD) = Z_iL_i \exp(-Z_iL_i) \approx Z_iL_i \quad (5)$$

where Z_i is the hazmat train accident rate per mile per shipment and L_i is the segment mileage.

The probability that a hazmat train accident would cause at least one tank car to release its contents, denoted as $P_i(X_R|\text{TD})$, can be modeled with Equation 6. This equation considers heterogeneous tank car derailment and release probabilities at different train positions. For example, suppose that a tank car is located at the jth position of a train. If this train is derailed on the ith track segment, the probability of derailing for this tank car is denoted as $\text{PD}_i(j)$. After this tank car is derailed, its release probability is represented by $\text{CPR}_i(j)$. Assuming that the releases of different tank cars are independent of each other, the probability of at least one tank car release in a train accident is equal to one minus the total probability that none of the derailed tank cars release contents:

$$P_i(X_R|TD) = 1 - \prod_{j=1}^{J}[1 - \text{PD}_i(j) \times \text{CPR}_i(j)] \quad (6)$$

where

$\text{PD}_i(j)$ = derailment probability of a tank car at the jth position of a train when this train is involved in an accident on the ith track segment,
$\text{CPR}_i(j)$ = conditional probability of release of a derailed tank car, and
J = total tank cars in a train.

Furthermore, position-dependent car derailment probability is estimated as follows (*22, 23*):

$$\text{PD}_i(j) = \sum_{g=1}^{L}\left\{\text{POD}_i(g) \times \sum_{x=j-g+1}^{L-g+1}\text{PN}_i(x)\right\} \quad (7)$$

where

$\text{POD}_i(g)$ = point-of-derailment probability for the gth position of a train if this train is involved in an accident on the ith track segment,
$\text{PN}_i(x)$ = probability of derailing x cars in a train accident on the ith segment, and
L = train length (total vehicles in a train, including locomotives).

Finally, based on Equations 1 to 7, route-specific railroad hazmat transportation risk given a number of train shipments (M) is expanded as follows:

$$R_{\text{route}} \approx M\sum_{i=1}^{N}\left[Z_iL_i\left\{1 - \prod_{j=1}^{J}\left[1 - \sum_{g=1}^{L}\left\{\begin{matrix}\text{POD}_i(g)\\ \times \displaystyle\sum_{x=j-k+1}^{L-g+1}\text{PN}_i(x)\end{matrix}\right\} \times \text{CPR}_i(j)\right]\right\}C_i\right] \quad (8)$$

The next section introduces the estimation of the parameters in the risk model.

PARAMETER ESTIMATION IN RISK MODELING

Train Accident Rate

Most incidents of hazardous materials release occur in train derailments (*24*). Therefore, this study focused on derailment-caused hazmat transportation risk analysis. However, the generalized methodology can be adapted to other accident types (e.g., collisions, grade crossing incidents) in future research. The latest freight train derailment rates were developed as a function of FRA track class, method of operation, and annual traffic density (*25*). That study was based on data from 2005 to 2009. In recognition of declining train derailment rates (*26*), a temporal adjustment factor is used to extrapolate future derailment rates. Liu found an average of 5.6% in annual declination rate in Class I main-line freight train derailment rates from 2000 to 2014 (*26*). Assuming that this trend continues, a statistical model can be used to estimate the freight train derailment rate now and in the near future. On the basis of these previous studies, the train derailment rate is estimated with Equation 9 as follows:

$$Z = \exp\begin{pmatrix} 0.9201 - 0.6649X_{\text{trk}} \\ -0.3377X_{\text{moo}} - 0.7524X_{\text{den}} \end{pmatrix}(1-5.6\%)^{T_i - 2009} \quad (9)$$

where

Z = estimated freight train derailment rate per billion gross ton-miles,
X_{trk} = FRA track class (1 to 5),
X_{moo} = method of operation (1 for signaled track territory, 0 for nonsignaled),
X_{den} = annual traffic density level [1 for ≥20 million gross tons (mgt), 0 for < 20 mgt], and
T_i = year (for example, T_i is equal to 2014 for year 2014).

Segment-specific hazmat traffic flow data are proprietary to railroads and generally not available to the public. It has been assumed that there is no statistical difference in derailment rate between hazmat trains and other types of trains (*27*). Therefore, this research used the average derailment rate for all freight trains as a proxy for the hazmat train derailment rate. A possible future research direction is estimation of hazmat train derailment rates when those data are available.

Point of Derailment

Point of derailment (POD) is the position where the vehicle (locomotive or rail car) is initially derailed. The first vehicle (generally the lead locomotive) is frequently the POD in a train derailment (about 8% of Class I main-line freight train derailments had the POD in the first vehicle). Previous studies found that the POD affects the number of vehicles derailed, all other factors being equal (*9, 10*). To account for different train lengths, the normalized POD was calculated by dividing POD by train length. Applying FRA train derailment data between 2002 and 2011, the best fit for the normalized POD distribution (all accident causes combined) is a Beta distribution, Beta (0.6793, 0.8999) ($P = .48 > .05$ with the Kolmogorov–Smirnov test). Given a train length L, the probability that the POD is at the gth position, POD(g), is estimated with the following equation:

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

where $F()$ is the cumulative density distribution of the fitted normalized POD distribution and L is the train length (total cars in a train).

For example, the estimated POD ($g = 1$) is 0.040 for a 100-car train ($L = 100$), and POD ($g = 2$) is 0.024 according to the fitted Beta distribution. Therefore, there is 4.0% chance that the derailment initiates from the first unit in a train (i.e., lead locomotive) and a 2.4% chance that the derailment initiates from the second car. Any car may be the POD, although with differing probabilities.

Number of Cars Derailed

The number of locomotives or rail cars derailed is frequently used in railroad safety analysis because of its relationship with accident kinetic energy (*24*). The total cars (including locomotives) derailed is affected by accident cause (*27, 28*), accident speed (*22, 23, 28*), train length (*22, 23*), and POD (*9, 10*). The statistical model for estimating train accident severity was developed by Saccomanno and El-Hage (*22, 23*). The probability distribution of the number of cars derailed given the POD is estimated as

$$\text{PN}_i(x) = \frac{\dfrac{\exp(M)}{1+\exp(M)}\left[\dfrac{1}{1+\exp(M)}\right]^{x-1}}{1-\left[\dfrac{1}{1+\exp(M)}\right]^{L-g+1}} \quad (11)$$

$$M = a + b \times \ln(V) + c \times \ln(L_r) + d \times I(\text{POD}) \quad (12)$$

where

$\text{PN}_i(x)$ = probability that x cars are derailed given the POD on the ith segment;
V = accident speed (mph);
L_r = residual train length, defined as the number of cars between the POD and the train end ($L_r = L - g + 1$);
I(POD) = 1 if the POD is a loaded car and 0 otherwise;
a = 1.215 (U.S. freight train derailment data from 2002 to 2011, the same data used for all following parameters);
b = −1.206;
c = 0.004; and
d = −0.312.

Conditional Probability of Release of Derailed Tank Car

The Association of American Railroads (AAR) and Railway Supply Institute (RSI) have maintained an industrywide tank car safety database since the 1970s. This database records detailed information about the design, accident speed, and release status of each derailed or damaged tank car in a train accident. Although this proprietary database is not publicly available, AAR–RSI periodically publishes average tank car release probabilities. In 2015, the U.S. Department of Transportation (DOT) specified a new tank car design (DOT-117) for transporting flammable liquids. This type of tank car has a head and shell thickness of 0.5625 in., with jacket, full-height head shields, and top fitting protection. Its release probability is 0.042 (for all quantities of release). This means that an average of four of these tank cars are expected to release contents given 100 derailed or damaged tank cars of this type. The CPR statistics published by AAR were based on train derailments at 26 mph (*29*). To the author's knowledge, the only published speed-dependent CPR was estimated by Kawprasert and Barkan (*18*). They found that a linear function can approximate the relationship between CPR and derailment speed, all else being equal. Their analysis was built on a recent study by AAR–RSI. RSI and AAR expect to publish updated speed-dependent CPRs in the near future, at which time their forthcoming tank car safety statistics will be used in a revised risk model. Future research should be directed toward a better understanding of tank car safety performance under specified accident characteristics.

Consequence of Tank Car Release Incident

Population in the affected area is a common metric in previous studies (*30, 31*). The hazard exposure model in the U.S. DOT emergency response guide recommends a 0.5-mi-radius circle as an estimate of the affected area for a fire caused by release of flammable hazardous materials (*32*). Once the affected area is determined, the number of people affected can be estimated by multiplying the size of the affected area by the average population density within the affected area. In addition to affected population, environmental impact, infrastructure and rolling stock damage, train delay, and loss of productivity may be among the consequences of a release incident. Quantifying these consequences would require a detailed, case-by-case assessment based on infrastructure and operating characteristics. To illustrate the methodology, this paper focuses on the risk measured in terms of the number of people who would potentially require evacuation or protection. Use of this risk measure is aligned with current evacuation practices in the wake of a hazmat release. Future research can adapt the methodology to account for other consequences, such as traffic delay, environmental impact, and property damage cost.

DECISION SUPPORT TOOL

The sophisticated risk analysis algorithms in this work have been built into an automated risk calculator, called the railroad hazmat transportation risk analyzer (RHTRA). RHTRA is coded on the Visual Basic application platform, which can run on Microsoft Excel. RHTRA accepts train-specific factors, including number of vehicles in a train (total locomotives and rail cars), number of tank cars, position of tank cars, train speed, and tank car safety design. It also accepts track-specific factors such as FRA track class, method of operation, annual traffic density, segment mileage, and population density along each segment. According to the methodology described above, RHTRA automatically computes segment-specific, accident-caused hazmat transportation risk and sums them to obtain a route-specific risk. The tool accounts for a variety of train configurations and tank car placement scenarios. Figure 2 illustrates the structure of RHTRA.

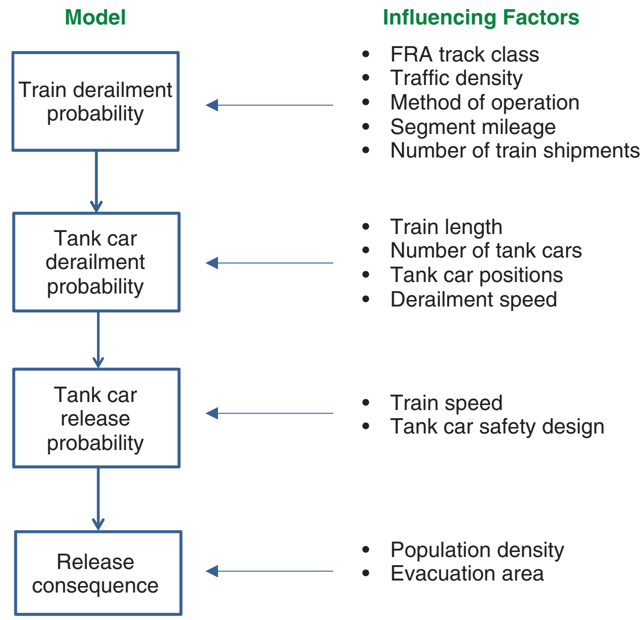

FIGURE 2 Decision support tool flowchart.

NUMERICAL EXAMPLE

This section uses numerical examples to illustrate the application of the model. The transportation risk for unit trains is compared for several types of mixed trains.

Probability of Release Incident per Train Derailment

Three derailment speeds are considered—25, 40, and 60 mph—which correspond to the maximum freight train operating speeds on FRA Track Classes 2, 3, and 4, respectively. Four types of mixed trains are considered, having 50 tank cars, 35 tank cars, 20 tank cars, or five tank cars, respectively, per train (all cars conforming to DOT-117, equivalent to the unit train considered above). In all mixed train configurations, three types of tank car placement scenarios are considered. In the first scenario, all tank cars are in positions that are the least prone to derailment. In the second scenario, all tank cars are randomly distributed in the train. In the third scenario, all tank cars are in positions most likely to derail. Thus, if a train has 25 crude oil tank cars, it also has 75 other types of rail cars. In general, these cars may include other types of hazardous materials. For simplicity, this study assumes that all the non-crude-oil tank cars in a mixed train do not contain other cargo that may have interactive effects with crude oil in a train derailment. For ease of comparison, the same total train length and number of locomotives for unit trains in comparison with mixed trains are considered. For example, a unit train has three head-end locomotives, one buffer car, and 100 tank cars (all tank cars conforming to DOT-117).

The position-dependent car derailment probability for a train derailment is derived with Equation 7 (Figure 3). For example, for the 50th car in the train, its derailment probability is about 0.17 at 25 mph, meaning that there is a 17% chance that this car will be derailed if its train is derailed. This probability will increase to 0.27 if the speed increases to 50 mph. Figure 3 shows that certain train positions have higher derailment probabilities than others. This finding is consistent with that of several previous studies (*9, 10, 22, 23*). Given the same train position, the higher the speed, the more likely this car will be derailed, all else being equal.

Given train configuration, tank car placement, and speed, the probability of at least one tank car release per train derailment can be estimated. For example, if a 35-tank-car hazmat train is derailed at 25 mph, and if all tank cars are in positions most prone to derailment, the probability that at least one tank car will release in a train derailment is 0.243 (Table 1). Table 1 presents the scenario-specific release probability by train configuration, speed, and tank car placement. The following are found from these calculations:

- A higher derailment speed results in a higher probability of a release incident after a train is derailed across all train configurations and tank car placement scenarios because a higher train speed increases tank car derailment probability as well as the release probability of a derailed tank car.
- Placing tank cars in positions that are less likely to derail reduces hazmat transportation risk. For example, at 40 mph, a 35-tank-car

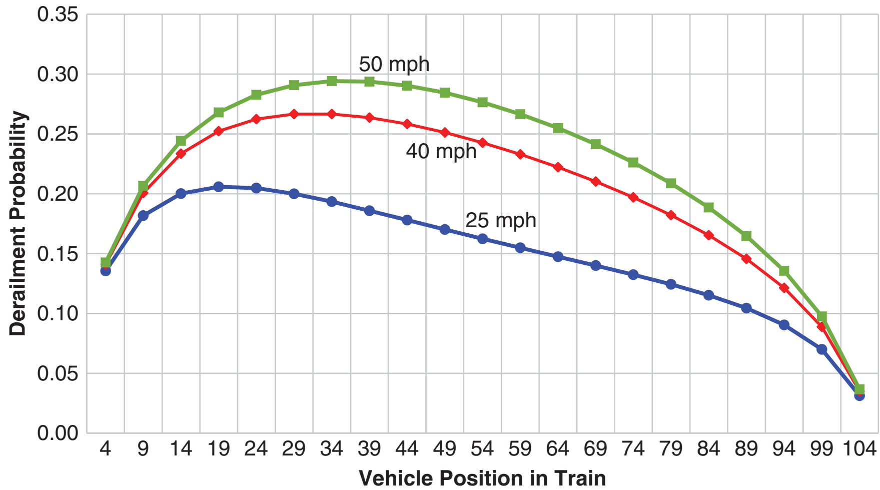

FIGURE 3 Position-dependent vehicle derailment probability per train derailment.

mixed train has a probability of a release incident (at least one tank car releases contents) of 0.274 if this train is derailed, given that all tank cars are in positions that are the least prone to derailment (best-case placement scenario). This probability increases to 0.447 if all these tank cars are in positions that are the most likely to derail (worst-case placement scenario). Changing tank car positions affects tank car derailment probability in a train derailment, affecting the risk.

- Shipping tank cars in mixed trains instead of unit trains would lead to a reduction in release probability per train derailment. For example, at 40 mph, a 100-car unit train derailment is 74% likely to result in a release incident. In comparison, the chance of a release per derailment for a 35-tank mixed train is between 27% and 45% at the same speed—depending on placement scenarios—because having fewer tank cars in a train reduces the probability that a tank car is derailed *after* train derailment occurs, reducing its release risk.

The analysis above does not consider that more mixed-train shipments are needed to transport the same number of hazmat carloads as a single unit train shipment. Although for each train derailment, fewer tank cars per train can reduce tank car derailment probability, which reduces the release risk, the additional shipments increase train traffic exposure and thus may increase the probability of train derailment for the total shipment. The next section addresses this issue.

Route Transportation Risk by Train Configuration

This section addresses the trade-off between hazmat train derailment frequency and severity through the development of an illustrative route-specific risk analysis. All the results can be generated with the decision support tool RHTRA within seconds. To demonstrate the calculation process, a simplistic numerical example is developed as follows. The analytical tool is applicable to all other routes or networks. Suppose there are three track segments with different characteristics (hypothetical and for illustration only):

Segment 1. FRA Track Class 2, 5-mi-long, nonsignaled, less than 20 mgt per year, 1,000 people within the evacuation zone.

Segment 2. FRA Track Class 3, 10-mile-long, signaled, less than 20 mgt per year, 750 people within the evacuation zone.

Segment 3. FRA Track Class 4, 20-mi-long, signaled, more than 20 mgt per year, 250 people within the evacuation zone.

TABLE 1 Probability of Release Incident After Train Derailment

Derailment Speed (mph)	Tank Car Position	One Unit Train with 100 Crude Oil Cars	50 Crude Oil Cars per Train	35 Crude Oil Cars per Train	20 Crude Oil Cars per Train	5 Crude Oil Cars per Train
25	Least prone to derailment	0.460	0.210	0.135	0.065	0.010
	Randomly distributed		0.265	0.194	0.116	0.030
	Most prone to derailment		0.316	0.243	0.151	0.041
40	Least prone to derailment	0.741	0.418	0.274	0.135	0.019
	Randomly distributed		0.493	0.377	0.237	0.066
	Most prone to derailment		0.561	0.447	0.292	0.083
50	Least prone to derailment	0.847	0.521	0.359	0.182	0.026
	Randomly distributed		0.609	0.482	0.313	0.090
	Most prone to derailment		0.682	0.560	0.380	0.113

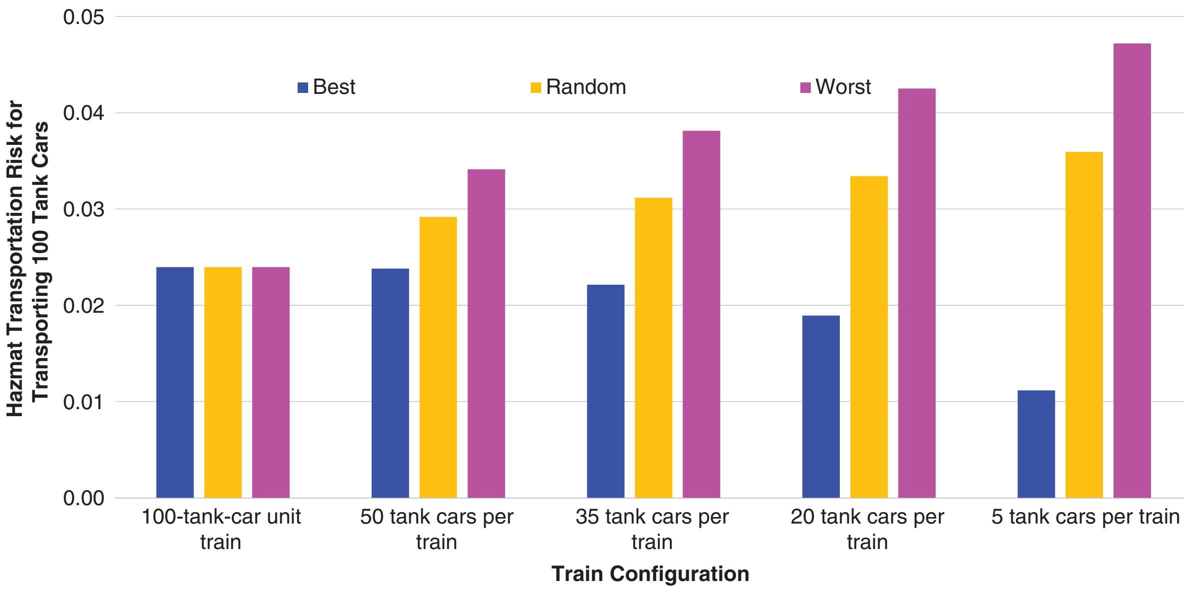

FIGURE 4 Illustrative risk comparison by train configuration and tank car placement on hypothetical route. "Best" means that all tank cars are in positions least prone to derailment. "Random" means that tank cars are randomly distributed in the train. "Worst" means that all tank cars are in positions most prone to derailment.

Figure 4 compares the route risk by train configuration and tank car placement on this hypothetical three-segment route. The figure shows that if tank cars in mixed trains are placed randomly or in positions most likely to derail, distributing tank cars to multiple trains would increase the total route risk, because a higher train derailment likelihood related to additional shipments more than offsets the lower tank car derailment likelihood in a train derailment. However, if all the tank cars are in positions least prone to derailment, use of more mixed trains, each of which has fewer tank cars, would reduce the total risk because the reduction of derailment severity (in terms of tank car derailment probability) exceeds the increase in hazmat train derailment frequency associated with additional shipments. Whether unit trains have higher risks than mixed trains for the same traffic demand depends on the placement of tank cars. In practice, the tank car placement could be subject to a variety of engineering and operational factors (*9, 10*). This paper focuses on the risk implications of hazmat train configuration and tank car placement without fully addressing all the related engineering and financial impacts, which should be treated in separate future studies.

RESEARCH CONTRIBUTIONS

Contribution to Literature

This research developed a generalized methodology to evaluate and compare hazmat transportation risks in unit trains versus mixed trains for the same traffic demand. Which type of train has a higher risk depends on how the tank cars are placed in the mixed train. If all tank cars are in the positions least prone to derailment, the use of multiple mixed trains may lead to a lower risk than consolidating all tank cars into unit trains. Otherwise, if tank cars are in other positions, distributing tank cars to multiple trains may increase the risk. This is a new insight that was not discovered in the previous literature. Furthermore, this generalized methodology can be applied to all types of trains, track characteristics, and hazardous materials.

Contribution to Practice

The decision support tool developed in this research can be used to quantify route-specific risk for both unit train and mixed train shipments of hazardous materials. In practice, tank car placement might be subject to a variety of engineering and operational factors. Depending on the actual train makeup, the carrier can use the risk tool developed here to estimate route-specific risk, which can help carriers evaluate optimal risk management plans.

CONCLUSION

This research compared hazmat transportation risk in unit trains versus mixed trains according to an integrated, generalized train-specific risk analysis methodology. The analysis found that a unit train has a higher probability of a release incident per train derailment because the large number of tank cars in a unit train would increase tank car derailment probability and thus the risk. However, use of a unit train would also reduce the number of shipments if the same number of hazmat cars were shipped in multiple mixed trains. Overall, unless tank cars are in positions least likely to derail, use of unit trains may have a lower total risk. If all tank cars are placed in the lowest-probability derailment positions, distributing tank cars to multiple mixed trains would result in a lower risk level. Depending on tank car placement in a train, the decision maker can determine which type of train has a lower transportation risk.

LIMITATIONS OF CURRENT STUDY AND FUTURE RESEARCH

The following are limitations of this study and future research:

1. This research focused on 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 (*33*). Accounting for thermal-tear-caused tank car release risk is the next step in this work.
2. This research focused on in-transit risk by train configuration. The next step is to incorporate the effect of different train makeups on yard safety and operational efficiency, particularly the risk to employees in the yard related to increased switching activities if a unit train is replaced by multiple mixed trains.
3. The actual tank car placement in a train is subject to various operational and engineering factors (e.g., train dynamics). A further study can be developed to account for principal engineering and cost implications of changing tank car positions.
4. Because of data limitation, this study assumed that the releases of multiple tank cars in a train derailment are mutually independent. Future research can improve the risk analysis by considering possible correlations among multiple tank car releases.
5. This paper does not account for interactive effects between flammable liquids and other types of hazardous materials. Future research could model this type of risk when a train carries multiple types of hazardous materials.
6. Because of unavailable actual speed information, this study used the maximum speed by FRA track class to develop a preliminary risk analysis. The actual train speed should be built into a refined risk model in future research.
7. Finally, risk assessment involves the estimators of several input parameters. The statistical variances of these parameter estimators affect the variance of the risk estimator. The uncertainty propagation of risk estimators could be quantified with statistical and risk analysis techniques in future research (*34*).

ACKNOWLEDGMENTS

The author was funded by the Department of Civil and Environmental Engineering, the School of Engineering, and the Center for Advanced Infrastructure and Transportation, all at Rutgers University. The author thanks Shuting Zha for assistance with the analyses during the study. The author also thanks three anonymous reviewers for constructive comments on the draft of the paper.

REFERENCES

1. Association of American Railroads. Crude Oil by Rail. https://www.aar.org/Pages/Crude-Oil-Rail-Traffic.aspx. Accessed Oct. 28, 2016.
2. Association of American Railroads. U.S. Rail Crude Oil Traffic. November 2015. https://www.aar.org/BackgroundPapers/US%20Rail%20Crude%20Oil%20Traffic.pdf. Accessed July 25, 2016.
3. 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. https://doi.org/10.1016/j.jhazmat.2013.04.052.
4. 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,* No. 2374, 2013, pp. 102–110. https://dx.doi.org/10.3141/2374-12.
5. 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,* No. 2261, 2011, pp. 124–133. https://dx.doi.org/10.3141/2261-14.
6. 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. https://doi.org/10.1016/j.jhazmat.2008.01.120.
7. 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. https://doi.org/10.1016/j.jhazmat.2011.01.136.
8. *Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High Hazard Flammable Trains.* PHMSA-2012-0082 (HM-251). U.S. Department of Transportation, 2012.
9. Bagheri, M., F.F. Saccomanno, and L.P. Fu. Modelling Hazardous Materials Risks for Different Train Make-Up Plans. *Transportation Research Part E,* Vol. 48, No. 5, 2012, pp. 907–918. https://doi.org/10.1016/j.tre.2012.02.004.
10. 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. https://doi.org/10.1111/risa.12063.
11. 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. https://doi.org/10.1016/j.jhazmat.2008.09.121.
12. 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. https://doi.org/10.1016/j.jhazmat.2014.05.029.
13. *Railroad Safety Statistics: Preliminary Annual Report.* FRA, U.S. Department of Transportation, 2011.
14. Liu, X. Analysis of Collision Risk for Freight Trains in the United States. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2546, 2016, pp. 121–128. http://dx.doi.org/10.3141/2546-15.
15. 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,* No. 2289, 2012, pp. 154–163. https://dx.doi.org/10.3141/2289-20.
16. Liu, X., and C.T. Dick. Risk-Based Optimization of Rail Defect Inspection Frequency for Petroleum Crude Oil Transportation. *Transportation Research Record: Journal of the Transportation Research Board,* No. 2545, 2016, pp. 27–35. https://dx.doi.org/10.3141/2545-04.
17. 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,* No. 1742, 2001, pp. 25–33. https://dx.doi.org/10.3141/1742-04.
18. 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,* No. 2159, 2010, pp. 59–68. https://dx.doi.org/10.3141/2159-08.
19. 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.* 2010. https://doi.org/10.2139/ssrn.2397482.
20. *Crude Oil Transport: Risks and Impacts.* Issue Brief 3. Great Lakes Commission, Ann Arbor, Mich., 2015.
21. Kaplan, S., and B.J. Garrick. On the Quantitative Definition of Risk. *Risk Analysis,* Vol. 1, No. 1, 1981, pp. 11–27. https://doi.org/10.1111/j.1539-6924.1981.tb01350.x.
22. Saccomanno, F.F., and S.M. El-Hage. Minimizing Derailments of Railcars Carrying Dangerous Commodities through Effective Marshaling Strategies. *Transportation Research Record,* No. 1245, 1989, pp. 34–51.
23. Saccomanno, F.F., and S.M. El-Hage. Establishing Derailment Profile by Position for Corridor Shipments of Dangerous Goods. *Canadian Journal of Civil Engineering,* Vol. 18, No. 1, 1991, pp. 67–75. https://doi.org/10.1139/l91-009.

24. Barkan, C., C.T. Dick, and R. Anderson. Railroad Derailment Factors Affecting Hazardous Materials Transportation Risk. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1825, 2003, pp. 64–74. https://dx.doi.org/10.3141/1825-09.
25. 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.
26. 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,* No. 2476, 2015, pp. 119–125. http://dx.doi.org/10.3141/2476-16.
27. Anderson, R.T., and C.P.L. Barkan. Railroad Accident Rates for Use in Transportation Risk Analysis. *Transportation Research Record: Journal of the Transportation Research Board,* No. 1863, 2004, pp. 88–98. https://dx.doi.org/10.3141/1863-12.
28. 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. https://doi.org/10.1016/j.aap.2013.04.039.
29. *Hazardous Materials: Enhanced Tank Car Standards and Operational Controls for High-Hazard Flammable Trains. Comments on PHMSA-2012-0082 HM 251.* Association of American Railroads, Washington, D.C., 2014.
30. Erkut, E., and V. Verter. A Framework for Hazardous Materials Transport Risk Assessment. *Risk Analysis,* Vol. 15, No. 5, 1995, pp. 589–601.
31. Erkut, E., and V. Verter. Modeling of Transport Risk for Hazardous Materials. *Operations Research,* Vol. 46, No. 5, 1998, pp. 625–642. https://doi.org/10.1287/opre.46.5.625.
32. *Emergency Response Guidebook.* U.S. Department of Transportation, 2016.
33. Barkan, C.P.L., X. Liu, and M.R. Saat. Research on Enhanced Tank Car Design Improves the Safety of Rail Transport of Petroleum Crude Oil and Alcohol. *TR News,* No. 298, 2015, pp. 41–43.
34. Hoffman, F.O., and J.S. Hammonds. Propagation of Uncertainty in Risk Assessments: The Need to Distinguish Between Uncertainty Due to Lack of Knowledge and Uncertainty Due to Variability. *Risk Analysis,* Vol. 14, No. 5, 1994, pp. 707–712. https://doi.org/10.1111/j.1539-6924.1994.tb00281.x.

All views and any errors are the author's.

The Standing Committee on Freight Rail Transportation peer-reviewed this paper.