RISK COMPARISON OF TRANSPORTING HAZARDOUS MATERIALS IN UNIT TRAINS VERSUS MIXED TRAINS

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ABSTRACT
This research develops an integrated, generalized risk analysis methodology to compare hazardous materials transportation risk in unit trains versus mixed trains for the same amount of traffic demand. The risk methodology accounts 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. Using these inputs, the methodology estimates train derailment rate, the probability of tank car derailment and release, and release consequence by train configuration. The analysis shows that tank car positions affect the risk comparison between unit trains and mixed trains in transporting hazardous materials. In particular, if all tank cars are in the positions that are the least prone to derailment, distributing tank cars to multiple unit trains can reduce the overall risk. Otherwise, consolidating tank cars into unit trains would lead to a lower risk. The methodology has been implemented into a computer-aided decision support tool that automatically calculates the risk values under different track, rolling stock, and operational characteristics.

Keywords: Hazardous Materials, Railroad, Unit Train, Mixed Train, Risk Analysis

1 INTRODUCTION

There are over two million tank-car loads of hazardous materials (hazmat) transported annually by rail in the United States. Recently, the boom in the 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 around 412,000 carloads of crude oil (*1*).

Differing from roadway transport that involves a single tank trailer, a train could carry multiple hazmat cars. At present, railroads extensively use unit trains (which may contain 50 to 120 loaded hazardous materials cars) to ship crude oil, sometimes hauling approximately 3 million gallons of crude oil per train (*2*). In addition to unit trains, a train may contain a mix of both hazardous materials cars and non-hazardous materials cars. In general, the use of unit trains is determined by shippers based on the loading capability at the origin facility.

Because different train configurations can be used to transport hazardous materials, it is important to understand their comparative risks. For example, consider that 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 multiple tank cars into one train would reduce the number of hazmat train shipments, thereby reducing hazmat train derailment frequency. On the other hand, this will likely increase the probability of a release incident if multiple tank cars are involved in the derailment.

To the best of my knowledge, there is little prior study that explicitly models and compares hazardous materials transportation risk in unit trains versus mixed trains for transporting the same number of hazmat cars. This knowledge gap motivates the development of the research in this paper. This research will develop a generalized risk analysis model that is adaptable to any train configuration. One particular application of the methodology is to understand to what degree placing hazmat cars in one unit train would affect the transportation risk, compared to placing these tank cars in multiple mixed trains.

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

2 LITERATURE REVIEW

Railroad hazardous materials risk management has received growing interest from academia and the transportation industry. The prior research effort focuses on different aspects of the risk management, such as infrastructure (*3, 4*), rolling stock (*5*), tank car safety enhancement (*6-8*), train makeup (*9,10*), or mitigation of release consequence (*11*). These previous studies synthetically structure railroad hazardous materials transportation as a multi-event, multi-factor risk management problem (Figure 1). This figure shows that a release incident is the end result of a five-step process, including 1) train derailment, 2) number of cars derailed, 3) number of hazardous materials cars derailed, and 4) number of hazmat cars releasing, as well as 5) release consequences.

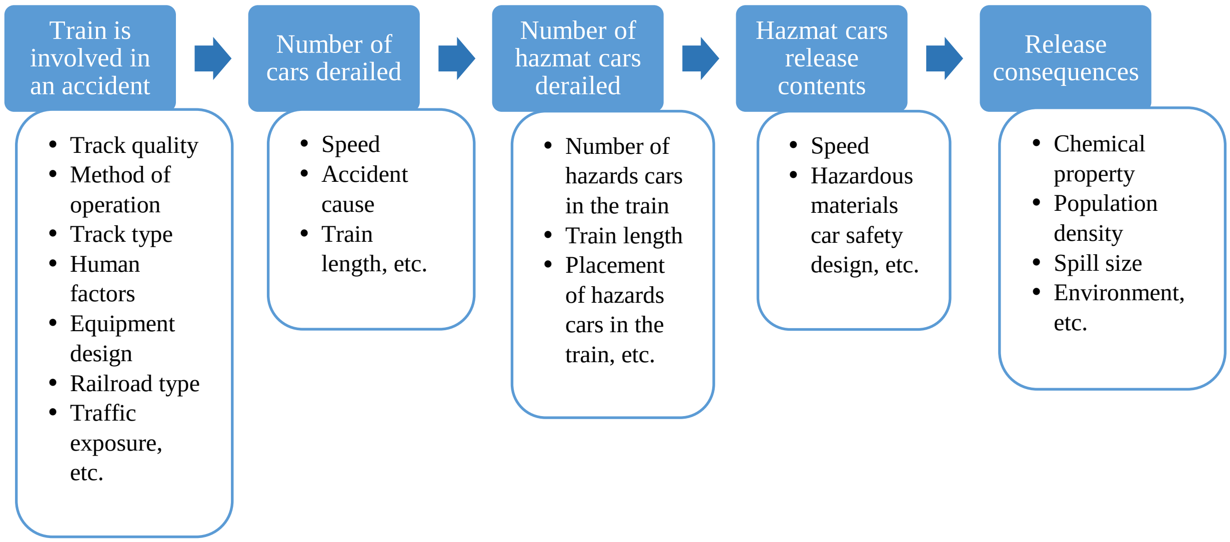

FIGURE 1 Event chain of a railroad hazardous materials release incident (adapted from (12))

There are several risk reduction strategies that 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-accident-caused release is beyond the scope of this paper). The USDOT Federal Railroad Administration (FRA) Rail Equipment Accident (REA) database records over 400 distinct accident causes (*13*). An analysis of historical train accident data found that derailments accounted for 72 percent of all types of accidents on mainlines (*14*), and over 70 percent 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*), or use of more advanced train control technology 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*) or 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 more robust tank car design can reduce tank car release probability, thereby reducing hazmat transportation risk (*6-8*). In addition, reducing train speed can mitigate accident impact on the tank car, thus decreasing the probability of release (*18*).
4) **Reduction of Hazmat Release Consequence.** The consequences of a release can be measured with different 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*).

3 KNOWLEDGE GAPS

While the majority of previous studies have focused on accident prevention and severity mitigation for a given train configuration, there is little prior work that compares 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 (2014) states, "mixed trains carrying crude oil are not adequately studied in risk analysis and emergency preparedness programs that address crude oil transport." This paper aims at narrowing this knowledge gap by developing an integrated, generalized risk analysis methodology, accompanied with 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 by rail, which predominantly travels by unit train, it is adaptable to all types of hazardous materials transported by various types of hazmat trains.

4 RESEARCH OBJECTIVE AND SCOPE

This research aims to contribute 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 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 mainlines. The hazmat release risk in yards is beyond of the scope of this paper. Also, this research centers on the risk aspect of train configuration, without accounting for all practical engineering and cost implications pertinent to train makeups. Furthermore, this research does not account for multiple-tank-car releases due to thermal tearing in a fire initiated by a flammable liquid release. This type of tank car release requires a different modeling process.

5 METHODOLOGY

Risk is the combination of the probability and the consequence (*20*). 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 second segment, respectively. The consequence of release on the second segment is C_2. Therefore, in this particular case, the expected consequence (risk) is $(1-P_1)P_2C_2$. Similarly, if a release occurs on the i^{th} segment, it means that there is no release incident on any of the prior segments (1, 2, 3,…, i-1). This paper assumes that a train shipment will terminate if a derailment occurs. Based on these considerations and assumptions, route-specific railroad hazmat transportation risk per train shipment is calculated as follows:

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

Where
R = accident-caused hazardous materials transportation risk
P_i = the probability of a release incident on the i^{th} segment
C_i = consequence of a release (e.g., affected population) on the i^{th} segment

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

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

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 ($P_i(X_R|TD)$):

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

Where
$P_i(TD)$ = probability of a hazmat train accident when this train traverses the i^{th} track segment
$P_i(X_R|TD)$ = probability of a release incident after a hazmat train accident occurs

Train accident rate (Z_i) is sufficiently small; therefore, based on 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 = hazmat train accident rate per mile per shipment
L_i = segment mileage

The probability that a hazmat train accident would cause at least one tank car to release its contents, denoted as $P_i(X_R|TD)$, can be modeled as follows using 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 j^{th} position of a train. If this train is derailed on the i^{th} track segment, the probability of derailing for this tank car is denoted as $PD_i(j)$. After this tank car is derailed, its release probability is represented by $CPR_i(j)$. 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:

$$P_i\left(X_R \mid TD\right) = 1 - \prod_{j=1}^{J}[1 - PD_i(j) \times CPR_i(j)] \tag{6}$$

Where:
$PD_i(j)$ = derailment probability of a tank car at the j^{th} position of a train, when this train is involved in an accident on the i^{th} track segment
$CPR_i(j)$ = conditional probability of release of a derailed tank car
J = total number of tank cars in a train

Furthermore, position-dependent car derailment probability can be estimated as follows (*21*, *22*):

$$PD_i(j) = \sum_{g=1}^{L}\left\{POD_i(g) \times \sum_{x=j-g+1}^{L-g+1} PN_i(x)\right\} \tag{7}$$

Where:
$POD_i(g)$ = point-of-derailment probability for the g^{th} position of a train if this train is involved in an accident on the i^{th} track segment
$PN_i(x)$ = probability of derailing x cars in a train accident on the i^{th} segment
L = train length (total number of 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) can be expanded as follows:

$$R_{route} \approx M \sum_{i=1}^{N}\left[Z_i L_i \left\{1 - \prod_{j=1}^{J}[1 - \sum_{g=1}^{L}\{POD_i(g) \times \sum_{x=j-k+1}^{L-g+1} PN_i(x)\} \times CPR_i(j)]\right\} C_i\right] \tag{8}$$

The next section will introduce the estimation of the parameters in the risk model.

6 PARAMETER ESTIMATION IN RISK MODELING

6.1 Train Accident Rate

The majority of hazardous materials release incidents occurred in train derailments (*23*). Therefore, this paper focuses 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 (*24*). That study was based on data from 2005 to 2009. In recognition of declining train derailment rates (*25*), a temporal adjustment factor is used to extrapolate future derailment rates. Liu found an average of 5.6 percent annual declining rate in Class I mainline freight train derailment rates from 2000 to 2014 (*25*). Assuming that this trend continues, a statistical model can be used to estimate the freight train derailment rate now and in the near future. Based on these previous studies, the train derailment rate can be estimated using Equation (9) as follows:

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

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 non-signaled)
X_{den} = annual traffic density level (1 for ≥ 20 million gross tons (MGT), 0 for < 20 MGT)
T_i = year (for example, T_i is equal to 2014 for year 2014)

Segment-specific hazmat traffic flow data is 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 (*26*). Therefore, this research used the average derailment rate for all freight trains as a proxy for the hazmat train derailment rate. One possible future research direction is to estimate hazmat train derailment rates when that data are available.

6.2 Point of Derailment, POD(g)

Point of derailment (POD) is the position where the vehicle (locomotive or railcar) is initially derailed. The first vehicle (generally the lead locomotive) is frequently the POD in a train derailment (around 8% of Class I mainline freight-train derailments had the POD in the first vehicle). Previous studies have 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 (NPOD) was calculated by dividing POD by train length. Using FRA train derailment data between 2002 and 2011, the "best-fit" for the NPOD distribution (all accident causes combined) is a Beta distribution, Beta (0.6793, 0.8999) (P = 0.48 > 0.05, using the Kolmogorov-Smirnov Test). Given a train length L, the probability that the POD is at the g^{th} position, POD(g), can be estimated using the following equation:

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

Where:
POD(g) = POD probability at the g^{th} position of a train
F() = cumulative density distribution of the fitted normalized POD distribution
L = train length (total number of cars in a train)

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

6.3 Number of Cars Derailed, PN(x)

The number of locomotives or railcars derailed is frequently used in railroad safety analysis because of its relationship with accident kinetic energy (*23*). The total number of cars (including locomotives here and thereafter) derailed is affected by accident cause (*26, 27*), accident speed

(*21, 22, 27*), train length (*21, 22*) and point of derailment (*9,10*). The statistical model for estimating train accident severity was first developed by Saccomanno and El-Hage (1989, 1991), and subsequently modified by Anderson (2005) and Bagheri et al. (2011), respectively. The probability distribution of the number of cars derailed given the POD can be estimated as:

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

$$M = a + b\times\ln(V) + c\times\ln(Lr) + d\times I(POD) \quad (12)$$

Where:
$PN_i(x)$ = the probability that x cars are derailed given the POD on the i^{th} segment
V = accident speed (mph)
L = train length (total number of cars in a train, including locomotives)
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, 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
d = -0.312

6.4 Conditional Probability of Release of A Derailed Tank Car, CPR

The Association of American Railroads (AAR) and Railway Supply Institute (RSI) has maintained an industry-wide tank car safety database since the 1970s. This database records detailed information regarding 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, the AAR-RSI periodically publishes average tank car release probabilities. In 2015, USDOT 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 inch, with jacket, full height head shields and top fitting protection. According to the Treichel, its release probability is 0.042 (for all quantities of release). This means that an average of 4 of these tank cars are expected to release contents given 100 derailed or damaged tank cars of this type. The CPR (conditional probability of release) statistics published by the AAR were based on train derailments at a speed of 26 mph (*28*). To the author's best 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, given all else being equal. Their analysis was built upon the a recent published study by the Association of American Railroads (AAR) and Railway Supply Institute (RSI). The RSI and AAR are anticipated 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 towards a better understanding of tank car safety performance under specified accident characteristics.

6.5 Consequence of a Tank Car Release Incident, C

Population in the affected area is a common metric in previous studies (*29, 30*). The hazard exposure model in the USDOT Emergency Response Guidebook (ERG) recommends a 0.5-mile-radius circle as an estimate of the affected area for a fire caused by flammable hazardous materials releases. 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 also be among the consequences of a release incident. Quantifying these consequences would require a case-by-case detailed assessment based on infrastructure and operating characteristics. To illustrate the methodology, this paper focuses only on the risk measured in terms of the number of people that 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 types of consequences, such as traffic delay, environmental impact, and property damage cost.

7 DECISION SUPPORT TOOL

The sophisticated risk analysis algorithms have been built into an automated risk calculator, called the *Railroad Hazmat Transportation Risk Analyzer* (RHTRA). The RHTRA is coded on the Visual Basic Application (VBA) platform, which can run on Microsoft Excel. The RHTRA accepts train-specific factors including number of vehicles in a train (total number of locomotives and railcars), 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. Based on 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 the RHTRA.

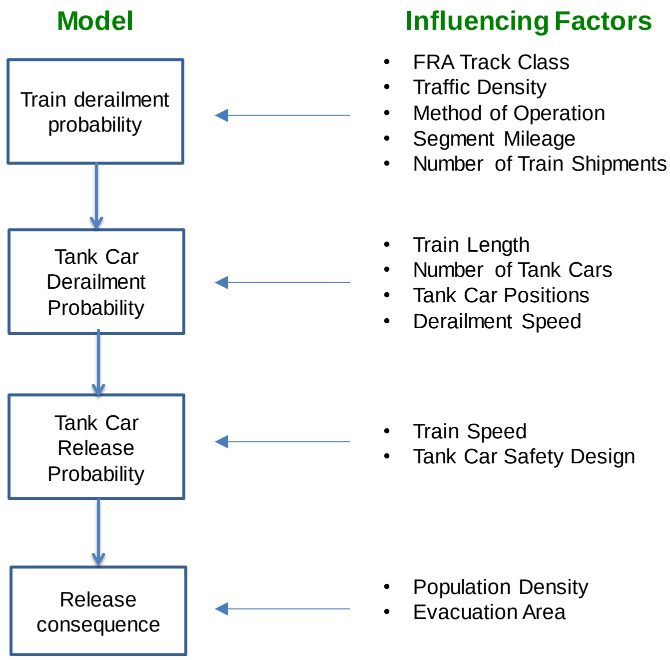

FIGURE 2 Decision support tool flow chart

8 NUMERICAL EXAMPLE

This section uses numerical examples to illustrate the application of the model. I compare the transportation risk for unit trains versus several types of mixed trains.

8.1 The Probability of a Release Incident per Train Derailment

I consider three derailment speeds - 25 mph, 40 mph, and 60 mph - which correspond to the maximum freight-train operating speeds on FRA track classes 2, 3, and 4, respectively. I consider four types of mixed trains, having 50 tank cars, 35 tank cars, 20 tank cars, or 5 tank cars, respectively, per train (all cars conforming to DOT-117, equivalent to the unit train considered above). In all train mixed train configurations, I consider three types of tank car placement scenarios. In the first scenario, all tank cars are in the positions 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 located in the positions most likely to derail. So if a train has 25 crude oil tank cars, it therefore also has 75 other types of railcars. In general, these cars may include other types of hazardous materials. For simplicity, this paper 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, I assume the same total train length and number of locomotives for unit trains in comparison with mixed trains. For illustration, consider that 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 can be derived using Equation (7) (Figure 3). For example, for the 50th car in the train, its derailment probability is around 0.17 at 25 mph, meaning that there is a 17 percent chance that this particular 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 several prior studies (*9*, *10*, *21*, *22*). Given the same train position, the higher the speed, the more likely this car will be derailed, all else being equal.

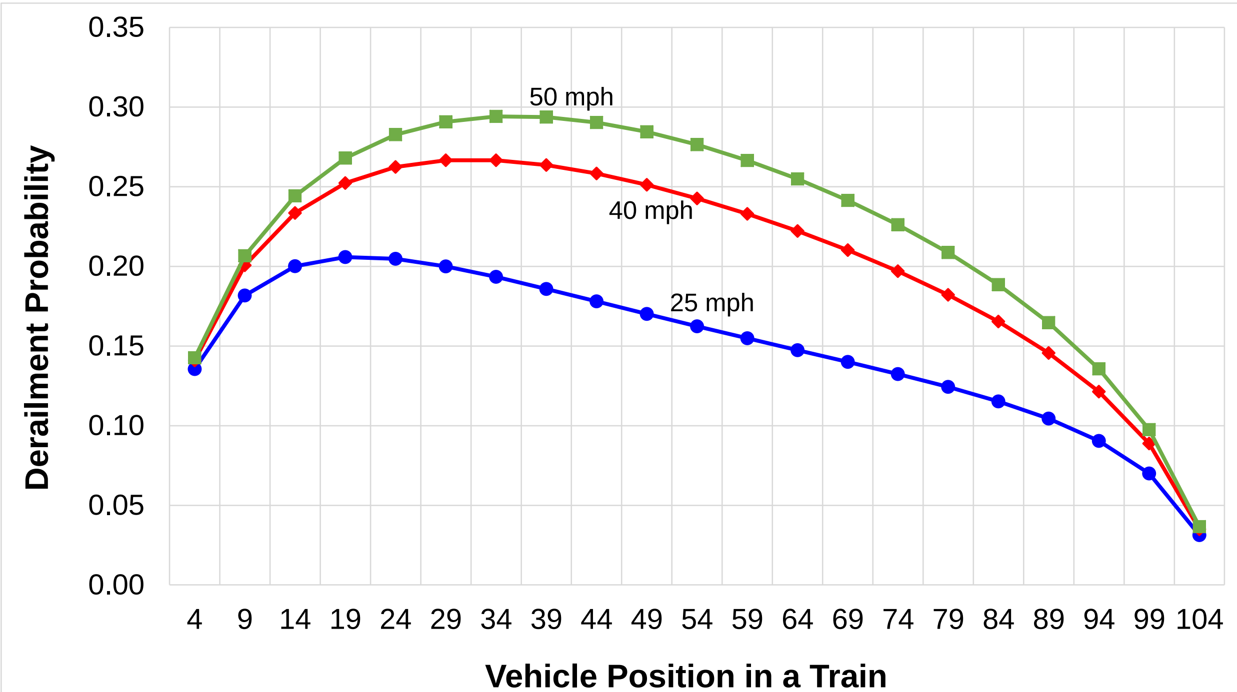

FIGURE 3 Position-dependent vehicle derailment probability per train derailment

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 the positions that are the most prone to derailment, the probability that at least one tank car would 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. From these calculations, it is found that:

- 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. This is because a higher train speed would increase 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 speed, a 35-tank-car 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 the positions that are the least prone to derailment ("best-case" placement scenario). This probability would increase to 0.447 if all these tank cars are in the 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, thereby 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. This is because having fewer tank cars in a train reduces the probability that a tank car is derailed after train derailment occurs, thereby reducing its release risk.

TABLE 1 The probability of a release incident after a train derailment occurs

Derailment Speed	Tank Car Positions	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 mph	The least prone to derailment	0.460	0.210	0.135	0.065	0.010
	Randomly distributed		0.265	0.194	0.116	0.030
	The most prone to derailment		0.316	0.243	0.151	0.041
40 mph	The least prone to derailment	0.741	0.418	0.274	0.135	0.019
	Randomly distributed		0.493	0.377	0.237	0.066
	The most prone to derailment		0.561	0.447	0.292	0.083
50 mph	The least prone to derailment	0.847	0.521	0.359	0.182	0.026
	Randomly distributed		0.609	0.482	0.313	0.090
	The most prone to derailment		0.682	0.560	0.380	0.113

Note that the analysis above does not account for the fact that more mixed-train shipments is 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, thereby reducing the release risk, the additional shipments increase train traffic exposure and thus may likely increase the probability of train derailment for the total shipment. The next section will address this issue.

8.2 Route Transportation Risk by Train Configuration

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

- Segment 1: FRA track class 2, 5 mile long, non-signaled, less than 20 MGT per year, 1000 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 mile long, signaled, more than 20 MGT per year, 250 people within the evacuation zone

Figure 4 compares the route risk by train configuration and tank car placement on this hypothetical three-segment route. It shows that if tank cars in mixed trains are placed randomly or in the positions that are the most likely to derail, distributing tank cars to multiple trains would increase the total route risk, because a higher train derailment likelihood due to additional shipments more than offsets the lower tank car derailment likelihood in case of a train derailment. However, if all the tank cars are in the positions that are the least prone to derailment, using more mixed trains, each of which has fewer tank cars, would actually 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 actual placement of tank cars. In practice, the actual tank car placement might 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.

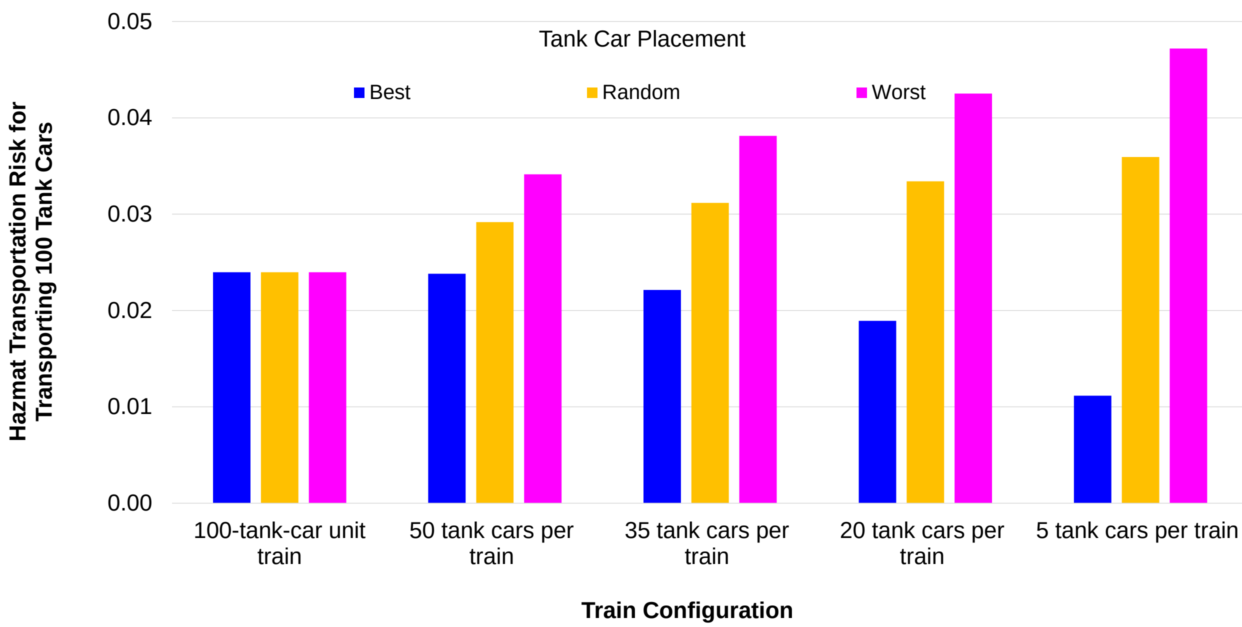

FIGURE 4 Illustrative risk comparison by train configuration and tank car placement on a hypothetical route

Notes: "Best" means that all tank cars are in the positions that are the least prone to derailment. "Random" mean that tank cars are randomly distributed in a train. "Worst" means that all tank cars are in the positions that are the most prone to derailment.

9 RESEARCH CONTRIBUTIONS

9.1 Contribution to the Literature

This research develops 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 the tank cars are located in the positions that are the least prone to derailment, 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 past literature. Furthermore, this generalized methodology can be applied to all types of trains, track characteristics, and hazardous materials.

9.1 Contribution to the 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. Based on the actual train make-up plan, the carrier can use the risk tool developed here to estimate route-specific risk. This may help them to evaluate optimal risk management plans.

10 CONCLUSION

This research compares hazmat transportation risk in unit trains versus mixed trains based on an integrated, generalized train-specific risk analysis methodology. The analysis finds 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 are shipped in multiple mixed trains. Overall, unless tank cars are in the positions that are the 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.

11 LIMITATIONS OF CURRENT STUDY AND FUTURE RESEARCH

1. This research focuses 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 (*31*). Accounting for thermal-tear-caused tank car release risk is the next step in this work.
2. This research focuses on in-transit risk by train configuration. The next step is to incorporate the effect of different train make-ups on yard safety and operational efficiency, particularly the risk to employees in yard due 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. Due to data limitation, this paper assumes that the releases of multiple tank cars in a train derailment are mutually independent. Future research can improve the risk analysis 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 can be conducted to model this type of risk when a train carries multiple types of hazardous materials.
6. Because of unavailable actual speed information, this paper uses 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 might be quantified using statistical and risk analysis techniques in future research (*32*).

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