



Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation



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ABSTRACT

Railroads play a key role in the transportation of hazardous materials in North America. Rail transport differs from highway transport in several aspects, an important one being that rail transport involves trains in which many railcars carrying hazardous materials travel together. By contrast to truck accidents, it is possible that a train accident may involve multiple hazardous materials cars derailing and releasing contents with consequently greater potential impact on human health, property and the environment. In this paper, a probabilistic model is developed to estimate the probability distribution of the number of tank cars releasing contents in a train derailment. Principal operational characteristics considered include train length, derailment speed, accident cause, position of the first car derailed, number and placement of tank cars in a train and tank car safety design. The effect of train speed, tank car safety design and tank car positions in a train were evaluated regarding the number of cars that release their contents in a derailment. This research provides insights regarding the circumstances affecting multiple-tank-car release incidents and potential strategies to reduce their occurrences. The model can be incorporated into a larger risk management framework to enable better local, regional and national safety management of hazardous materials transportation by rail.

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1. Introduction

More than two million carloads of hazardous materials were transported by North American railroads in 2012 [1]. Although hazardous materials accounts for only 6% of U.S. rail traffic and more than 99% of shipments safely reached their destinations without incident, this traffic is responsible for a major share of railroads' liability and insurance risk [2]. Recently, there has been particular interest in rail transport of flammable liquids such as petroleum and alcohol in response to the rapid growth in this traffic and several recent train accidents that resulted in large releases and have drawn industry, government and the public's attention.

Rail transport of hazardous materials differs from highway transport in several respects. Notably, rail transport involves trains of multiple cars, sometimes over 100 in a single train. Some or all

of these may be tank cars transporting hazardous materials. By contrast, highway transport generally involves only a single tank trailer. Unlike highway transport, derailment of a hazardous materials train may result in releases from multiple tank cars. In the event of a large, multiple-car release incident, there is the potential for considerable impact on human health, property, and the environment. Furthermore, such releases may be much more challenging for emergency response than a highway incident because of the large quantities involved. Several recent multiple-tank-car release incidents, such as the derailments in Schellebelle, Belgium in May 2013, Lac-Mégantic, Canada in July 2013, Aliceville, Alabama in November 2013, and Casselton, North Dakota in December 2013, underscore the importance of multiple-car release incidents.

The number of tank cars releasing per derailment is affected by a number of factors such as train length, derailment speed, accident cause, point of derailment (the position of the first car derailed), positions of tank cars in the train, and tank car safety design [3–10]. Previous analyses have focused on one or more of these factors under specific circumstances. For example, Bagheri et al. [10] estimated the probability of multiple-car releases assuming that all tank cars have equal release probability and are grouped together in the train. Their assumptions are suitable for certain

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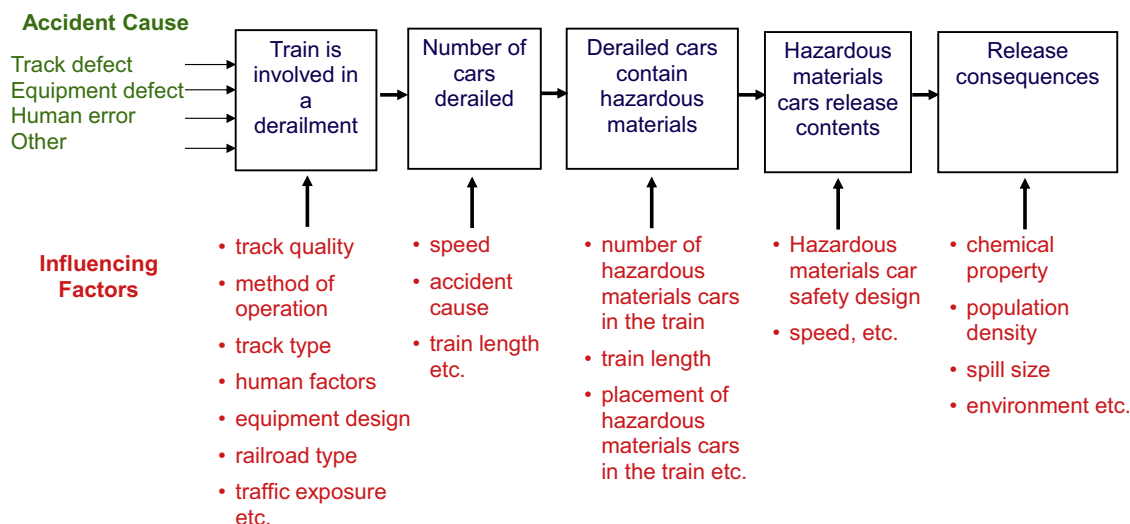


Fig. 1. Sequence of events leading to a hazardous materials release incident.

specific conditions; however, circumstances in which tank cars have different safety designs and may be distributed anywhere throughout the train require a more sophisticated approach.

In this paper, a generalized model is developed to estimate multiple-car release probability using the Law of Total Probability [11]. The model extends and generalizes previous models because it is applicable to any type of train configuration, tank car safety design and distribution of tank car positions in the train. We used this model to analyze the safety effectiveness of various strategies to reduce the occurrence of multiple-tank-car release incidents.

2. Literature review

Hazardous materials transportation risk assessment relies on estimation of the probability and consequences of a release incident [12–17]. Each element in the event chain of a hazardous materials release incident (Fig. 1) has been analyzed in previous studies. In this section, we briefly review and summarize these studies.

2.1. Freight-train derailment rate

Most major railroad hazardous materials release incidents occur as a result of train derailments. Attempts to relate derailment rate to infrastructure characteristics date back to the early 1980s. Nayak et al. [3] found that higher Federal Railroad Administration (FRA) track classes had lower train derailment rates, and a subsequent study by Treichel and Barkan [18] found a similar result that was later updated by Anderson and Barkan [19]. All of these studies found that higher FRA track classes had lower derailment rates. Higher track classes are required for higher operating speeds, thereby requiring a variety of more stringent maintenance and engineering safety standards [20]. In addition to FRA track class, Liu [21] analyzed two additional factors—method of operation and traffic density and it was found that all three factors are strongly correlated with train derailment rates. In Canada, Saccomanno et al. [22] analyzed train derailment rates by traffic volume, track type (single track versus multiple tracks), train speed and region and they also found that train derailment rate varies with infrastructure and traffic characteristics.

2.2. Number of cars derailed

Although the total damage costs of a derailment are sometimes used as a metric of derailment severity, number of cars derailed

is more appropriate for analysis of tank car safety and hazardous materials risk because of its closer relationship with derailment energy [23]. The total number of cars derailed is affected by accident cause [5,6,20,23–26], train speed [3,5,6,23,24,26], train length [3,5,6,24,26], and point of derailment [5,6,9,24,26].

2.3. Number of tank cars derailed

The number of tank cars derailed is related to the total number of cars (both tank and non-tank cars) derailed, and the number and placement of the tank cars in a train. Glickman et al. [7] assumed that the number of tank cars derailed follows a hyper-geometric distribution when tank cars were randomly placed in the train. Bagheri et al. [9,10] estimated the total number of tank cars derailed given their positions. Although the effects of tank car safety design and tank car position in the train have been considered independently in prior work, to our knowledge, no previous research has simultaneously accounted for both factors. One objective of this research is to develop a generalized model to estimate the total number of tank cars derailed and their probability of releasing that accounts for the type of tank car and its position in a train.

2.4. Number of tank cars releasing contents

Not all derailed tank cars release their contents. The Railway Supply Institute (RSI)—Association of American Railroads (AAR) Railroad Tank Car Safety Research and Test Project has developed a tank car accident database (TCAD) containing information on tank cars involved in accidents in the U.S. Using the current subset of this database, Treichel et al. [27] developed logistic regression models to estimate the conditional probability of release for nearly all common designs, as well as new designs that incorporate existing design features. Previous analyses have used an average release probability [7,10]; however, Barkan et al. [23] and Treichel et al. [27] found a strong effect of speed on both derailment severity and release probability of hazardous materials cars derailed. Kawprasert and Barkan [28] extended Treichel et al.'s analysis by accounting for the effect of derailment speed in estimating release probability.

2.5. Release consequence

The consequence of a hazardous material release can be expressed using several metrics, such as human impact (e.g. the

number of people potentially affected by a release, i.e. evacuees and/or casualties), monetary units for costs due to property damage, environmental damage, and litigation or other forms of financial impact [17,29,30]. The hazard area of a release incident is affected by a variety of factors including chemical properties, quantity released, rate of release, meteorological conditions and local terrain. Toxic vapors, pool fires, explosions, soil and groundwater contamination and ecological damage are among the hazard types that a hazardous materials release incident may pose, depending on the product released and circumstances of its release [31–35]. Previous studies have analyzed the generation, propagation and impact of these hazard types using pool fire modeling [32] and Gaussian plume modeling (GPM) for airborne chemicals [36]. Based on different hazard types, simulation tools have been developed to estimate the impact of a hazardous materials release [31,34]. Based in part on simulation analysis and historical data, the U.S. Department of Transportation Emergency Response Guidebook recommends first responders' initial isolation and protective action distances for specific chemicals and scenarios of release [37]. In addition to human impact, the consequences of a hazardous materials release could also include environmental clean-up cost [28], train delay cost and others [30]. Consequence analysis can be conducted using a Geographic Information System platform integrated with other databases such as census and track infrastructure data [38–40].

The surrounding natural and built environment at an accident location may also affect tank car derailment and release probabilities and consequences; however, the effects of these factors have not been quantitatively analyzed and therefore cannot be explicitly incorporated into our risk model at this time.

3. Methodology

Eq. (1) is used to estimate the probability distribution of the number of tank cars releasing after a train derailment occurs.

$$P(X_R) = \sum_{X_D=0} \left\{ \underbrace{P(X_R|X_D)}_{\text{Tank cars releasing}} \left\{ \sum_{X=1} \underbrace{P(X_D|X)}_{\text{Tank cars derailed}} \left[\sum_{K=1} \underbrace{P(X|K)}_{\text{All types of cars derailed}} \underbrace{\text{POD}(K)}_{\text{Point-of-derailment}} \right] \right\} \right\} \quad (1)$$

where K is the point of derailment; L is the train length (total number of locomotives and all types of railcars); X_D is the number of tank cars derailed; X_R is the number of tank cars releasing contents; L_T is the number of tank cars in the train; in order to estimate the probability distribution of the total number of tank cars releasing, the following distributions need to be estimated sequentially. In the following sections, each of them will be explained in more detail.

- (1) point-of-derailment (POD), the position of the first car derailed;
- (2) number of cars derailed (including both tank cars and other types of railcars and locomotives) given a POD;
- (3) number of tank cars derailed given the total number of cars derailed;
- (4) number of tank cars releasing given the total number of tank cars derailed.

3.1. Point of derailment, $\text{POD}(K)$

Point-of-derailment is the position of the first car derailed. The first vehicle (generally the lead locomotive) in the train is frequently the first to derail [24]. Previous studies found that, ceteris paribus, the nearer the POD is to the front of a train, the more cars derail [5,6,8,9,24]. Data used in this paper were from the FRA Rail Equipment Accident (REA) database from 2002 to 2011. The FRA REA database contains all accidents that exceeded a specified monetary threshold of damage costs to on-track equipment, signals, track,

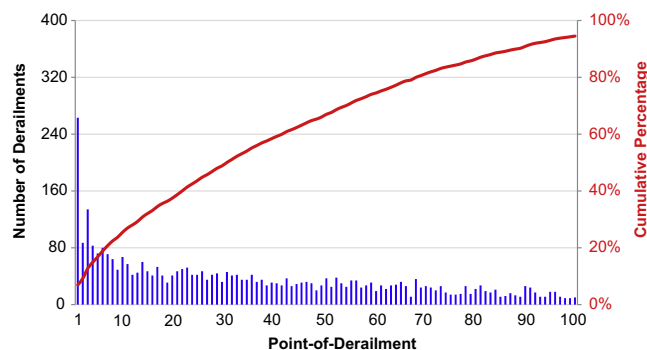


Fig. 2. Distribution of the point-of-derailment of 3812 Class I mainline freight-train derailments due to all causes, 2002–2011 (partial distribution of POD up to position 100 shown, accounting for 94% of all derailments analyzed).

track structures or roadbed. The reporting threshold is periodically adjusted for inflation, from \$5700 in 1990 to \$9900 in 2013 [41]. This research focuses on mainline, freight-train derailments on Class I railroads, a group of the largest U.S. railroads accounting for 69% of route miles and 88% of carloads transported in the U.S. [42]. The analysis showed that approximately 25% of train derailments had the POD in the first 10 positions of the train (Fig. 2).

To account for different train lengths, the normalized POD (NPOD) was calculated by dividing POD by train length [5,6]. Several probability distributions (beta, normal, logistic, weibull, uniform, gamma) were selected to fit the NPOD data. The goodness-of-fit of a fitted NPOD distribution was evaluated using the Kolmogorov–Smirnov (K–S) test [43]. The “best-fit” for the NPOD distribution (all accident causes combined) is a Beta distribution. This is consistent with prior research based on different study periods [5,6,24]. The beta distribution is a continuous probability

distribution defined on the interval $[0,1]$ and parameterized by two shape parameters. In the Kolmogorov–Smirnov (K–S) test, the P -value evaluates the goodness of fit of empirical data compared to a theoretical distribution. If the P -value is larger than 0.05, the distribution chosen to fit the data may be acceptable. Table 1 presents the “best” fitted NPOD distributions for several major derailment causes on U.S. railroads using the FRA REA database.

Given a train length L , the probability that the POD is at the K th position, $\text{POD}(K)$, can be estimated using the following equation:

$$\text{POD}(K) = F\left(\frac{K}{L}\right) - F\left(\frac{K-1}{L}\right) \quad (2)$$

where $\text{POD}(K)$ is the POD probability at the K th position of a train; $F()$ is the cumulative density distribution of the fitted distribution; L is the train length.

Broken rails and bearing failures are the leading track-related and equipment-related train derailment causes, respectively, on U.S. freight railroads [23,25]. Broken-rail-caused train derailments are more likely to have the POD in the front of a train, whereas the POD is approximately uniformly distributed for bearing-failure-caused train derailments (Fig. 3). That POD distributions differ by accident cause suggests that train accident analyses should account for specific causes; this will be discussed in the next section.

Table 1

Parameter estimates for fitting NPOD distributions for major derailment causes of freight-trains, Class I mainlines, 2002 to 2011.

Cause group	Description	Fitted distribution	P-value	Sample size
08T	Broken rails or welds	Beta (0.5519, 0.8576)	0.15	543
04T	Track geometry (excl. wide gauge)	Beta (0.8622, 0.7065)	0.23	281
12E	Broken wheels (car)	Beta (1.0497, 0.9372)	0.97	216
10E	Bearing failure (car)	Uniform (0, 1)	0.71	204
09H	Train handling (excl. brakes)	Beta (0.7348, 1.5488)	0.70	184
All causes		Beta (0.6793, 0.8999)	0.48	3812

Note: each accident cause group represents a set of similar accident causes (for more discussion of these groupings see Ref. [24]).

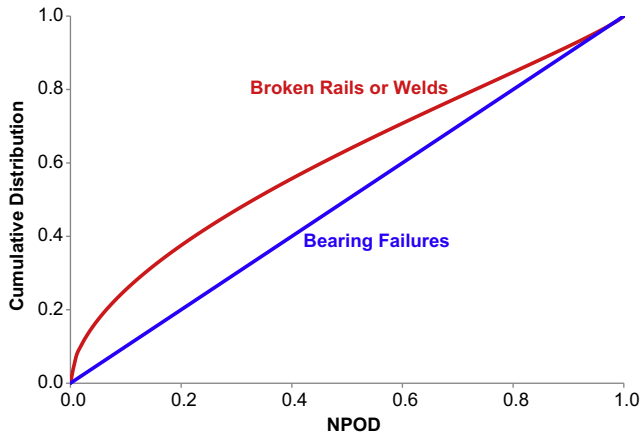


Fig. 3. Comparison of fitted NPOD distributions by major accident causes, Class I mainline freight-train derailments, 2002–2011.

3.2. Total number of cars derailed, $P(X|K)$

The number of cars derailed in a train derailment has been used as a metric for train derailment severity [5,6,23,25]. Fig. 4 shows the distribution of the number of cars derailed on U.S. Class I mainlines from 2002 to 2011. Approximately 24% of derailments resulted in a single car derailed. 50% resulted in five-or-fewer cars derailed, and the average number of cars derailed was approximately nine.

Derailment severity varies by accident cause [3,5,6,23–25]. We compared the distribution of derailment severity due to broken rails and bearing failures, respectively (Fig. 5). The average broken-rail-caused freight-train derailment severity was 13 cars, compared to an average of six cars derailed when the cause was bearing failure. Although bearing failures sometimes cause severe train derailments, 55% of them resulted in only a single car derailed. This difference in accident-cause-specific derailment severity is probably due in part to different POD distributions, and possibly different derailment dynamics. Broken rails caused more hazardous

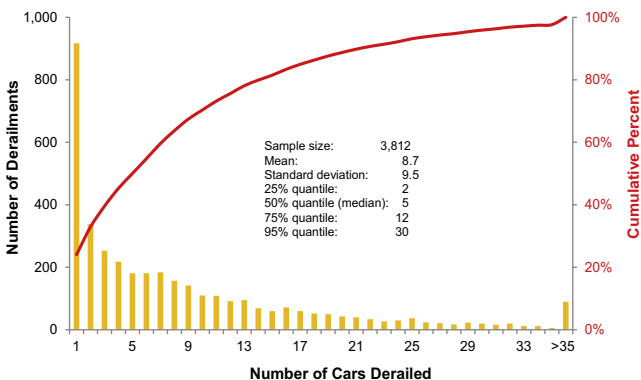


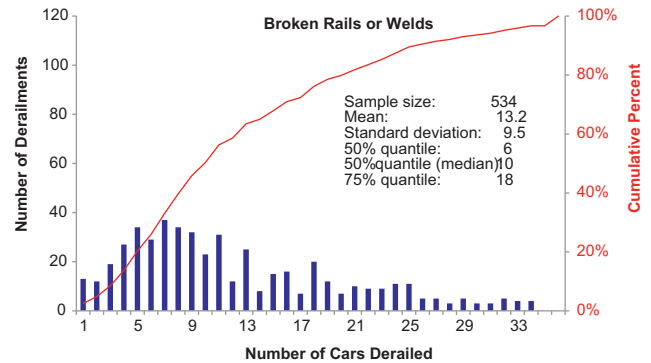
Fig. 4. Distribution of number of cars derailed per train derailment, Class I railroad freight-train derailments on mainlines, all accident causes combined, 2002 to 2011.

materials car releases than other causes. According to the FRA REA database, 438 hazardous materials cars released on U.S. railroads from 2002 to 2011, of which 106 (24%) were caused by broken rails. We used broken rails as an example to illustrate the methodology, but it can be adapted to other accident causes as well.

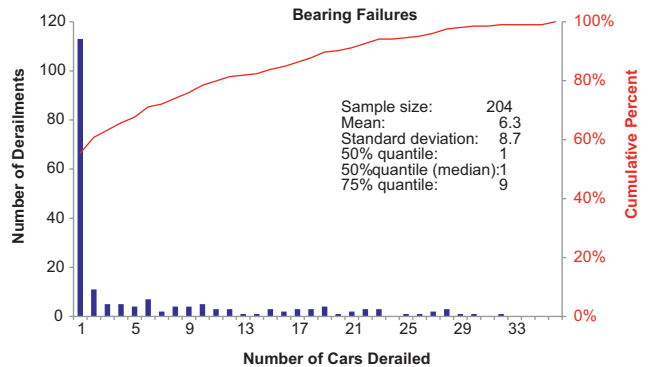
The statistical model for estimating train derailment severity was first developed by Saccomanno and El-Hage [5,6], and subsequently modified by Anderson and Barkan [24] and Bagheri et al. [9]. The probability of derailing a certain number of cars can be estimated using the following equation (model derivation is presented in Appendix A):

$$P(X|K) = \frac{\exp(Z) / [1 + \exp(Z)] [1 / 1 + \exp(Z)]^{X-1}}{1 - [1 / 1 + \exp(Z)]^{L-K+1}} \quad (3)$$

where $Z = a + b \times \ln(S) + c \times \ln(L_r) + d \times L_d$. The notations for S , L_r and L_d are presented in Appendix A. Based on the POD distribution (POD(K)) and the number of tank cars derailed given the POD ($P(X|K)$), the distribution of the total number of cars can be estimated. Then, we analyze the number of tank cars derailed given the total number of all types of cars derailed.



(a) Broken rails or welds



(b) Bearing failures

Fig. 5. Number of cars derailed in freight-train derailments due to (a) broken rails or welds, and (b) bearing failures, Class I mainlines, 2002–2011.

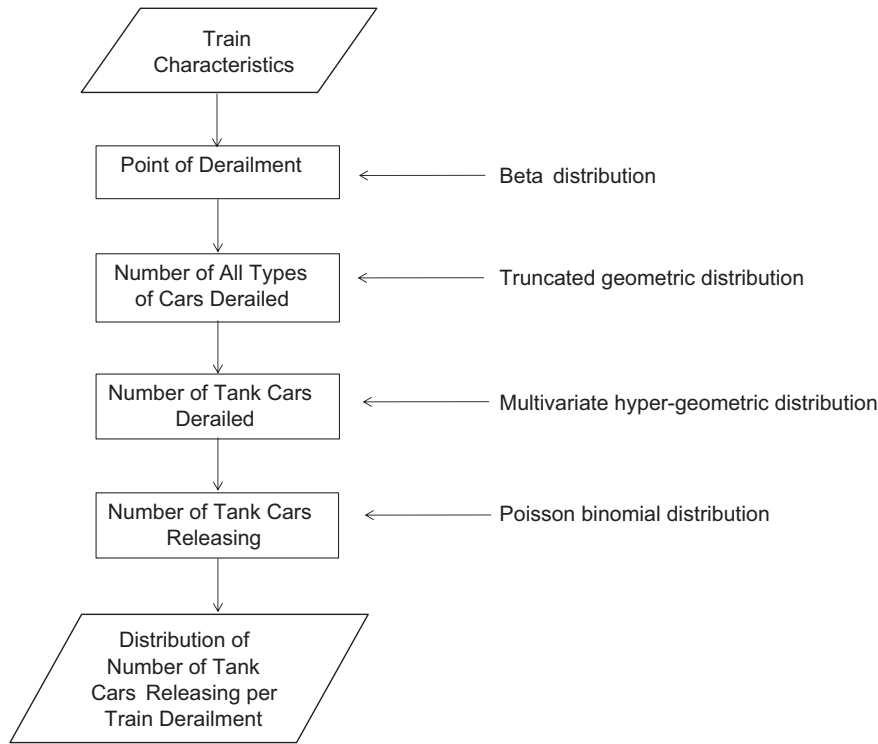


Fig. 6. Procedure for assessing the distribution of the number of tank cars releasing per train derailment.

3.3. Tank car derailment, $P(X_D|X)$

Depending on the placement and total number of tank cars in a train, a derailment may result in various numbers of tank cars derailing. Glickman et al. [7] assumed that tank cars were randomly distributed throughout the train and had the same release probability. They used a hyper-geometric distribution to calculate the probability distribution of tank car derailment. This paper extends Glickman et al.’s analysis by accounting for the derailment of different types of tank cars (different types may have different release probabilities [27]) using a multivariate hyper-geometric distribution. We adopt the same assumption as Glickman et al. [7] that tank cars are randomly distributed throughout the train. The multivariate hyper-geometric distribution of the number of tank cars derailed has the following expression:

$$P(X_{D1}, \dots, X_{Dm}|X) = \frac{\binom{T_1}{X_{D1}} \dots \binom{T_m}{X_{Dm}} \binom{L - \sum_{i=1}^m T_i}{X - \sum_{i=1}^m X_{Di}}}{\binom{L}{X}} \quad (4)$$

where X_{Di} is the number of the i th type of tank cars derailed; m is the types of tank cars in the train; X is the total number of cars (both tank and non-tank cars) derailed; T_i is the number of the i th type of tank cars in the train; L is the train length.

3.4. Tank car release, $P(X_R|X_D)$

The conditional probability of release (CPR) of a derailed tank car depends on its design characteristics and derailment speed [27,29,44–46]. Tank car release probability is a Bernoulli variable. The sum of Bernoulli variables with different probabilities follows a Poisson binomial distribution [47]:

$$P(X_R = k|X_{D1}, \dots, X_{Dm}) = \sum_{A \in F_k} \prod_{i \in A} P_i \prod_{j \in A^c} (1 - P_j) \quad (5)$$

where X_R is the number of tank cars releasing per train derailment; X_{Dm} is the number of the m th type of tank cars derailed; F_k is the set of all subsets of k integers selected from $\{1, 2, 3, \dots, X_{D1} + \dots + X_{Dm}\}$; A is the subset of F_k ; A^c is the complement of set A (i.e. $A^c = \{1, 2, 3, \dots, X_{D1} + \dots + X_{Dm}\}/A$); P_i is the conditional probability release of a specific type of tank car.

The probability mass function (PMF) of a Poisson binomial distribution can be derived using Poisson approximation [48], recursive formulae [49], normal approximation [50] or Fourier transformation [51]. A summary of the Poisson binomial distribution can be found in Hong [52].

4. Numerical example

In this section, we present a numerical example to illustrate the analytical procedure for assessing the probability distribution of the number of tank cars releasing per train derailment (Fig. 6).

We analyzed the safety benefits of a conventional non-jacketed DOT 111A100W1 tank car compared to an enhanced design. The DOT 111A100W1 is the most common type of tank car used for transporting flammable liquids in the United States [1]. In 2011, the Association of American Railroads (AAR) petitioned the Pipeline and Hazardous Materials Safety Administration to adopt more robust requirements for DOT-111 tank cars used to transport packing group I and II materials. That petition, P-1577, proposed a series of safety improvement options, such as top fittings protection, reclosing pressure relief valve, thicker tank car shell and head or an external jacket, and head shields [53]. Subsequently, AAR adopted an interchange standard (CPC-1232) with the same requirements applicable to tank cars ordered after October 1, 2011.

The CPC-1232 standard requires either a thicker tank shell and head; or a jacket. Both types of CPC-1232 compliant cars are required to be equipped with top fittings protection and a minimum half-inch, half-height head shield [53]. In this section, we compare the key design features and CPR of a conventional, non-jacketed, DOT 111A100W1 tank car, with those of a jacketed

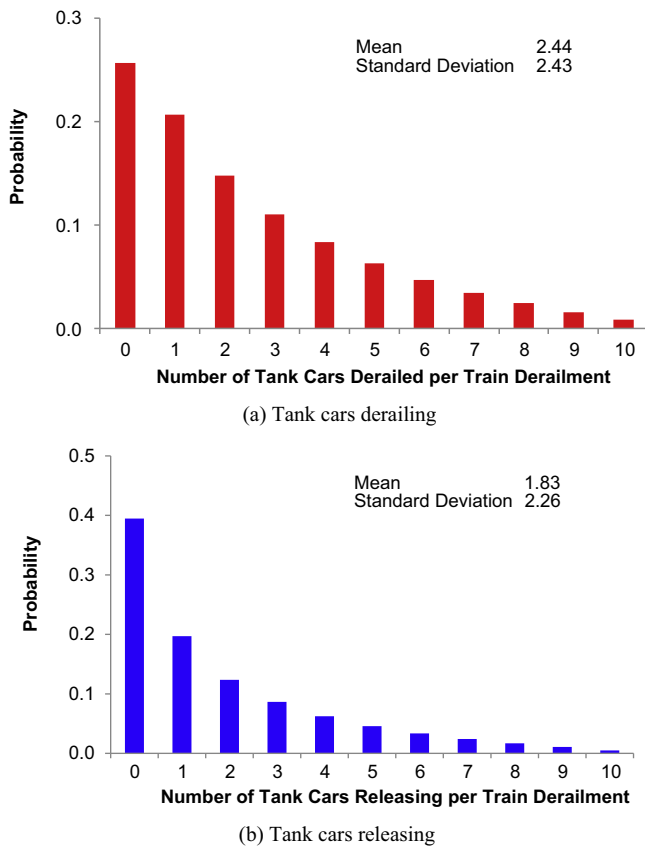


Fig. 7. Estimated probability distribution of the number of tank cars derailing and releasing per broken-rail-caused train derailment for an 82-car train with 10 conventional, non-jacketed DOT 111A100W1 tank cars.

CPC-1232 compliant tank car. The RSI-AAR Railroad Tank Car Safety Research and Test Project developed up-to-date statistics regarding release probability of a derailed tank car accounting for its safety design, derailment speed, the number of cars derailed, and the relative position of the tank car among all cars derailed [54].

In the baseline scenario, we assumed that the train has two head-end locomotives and eighty loaded cars, among which 10 are baseline conventional, non-jacketed DOT 111A100W1 tank cars. We also assumed that the train was derailed due to a broken rail, at a speed of 50 mph. The methodology can be adapted to other train configuration types and/or other accident causes. Fig. 7 shows the estimated distribution of the number of tank cars derailing and releasing based on these assumptions.

In this example, the probability of no tank car releasing is 0.39, the probability of releasing one tank car is 0.20 and the probability of two-or-more cars releasing per derailment is 0.41.

In the following sub-sections, we evaluate the effectiveness of several strategies, individually and in combination, to reduce the occurrence of multiple-tank-car release incidents. For comparison, the train operational information in the numerical example section above is used as the baseline scenario.

4.1. Train speed reduction

Train speed has a two-fold effect on the number of tank cars releasing. First, on average, lower speed derailments result in fewer cars derailed [3,5,6,23,24]. Second, as already discussed, lower derailment speed results in a lower release probability of a derailed tank car [27]. Fig. 8 compares the distribution of tank car releases by derailment speed. The train above derailing at 50 mph has a probability of releasing two-or-more tank cars of 0.41 and a mean

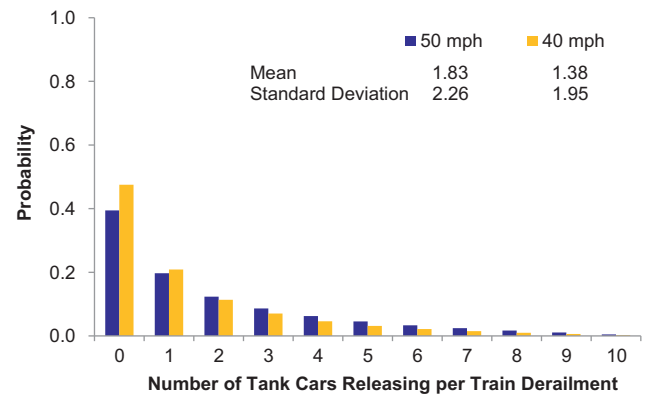


Fig. 8. Estimated probability distribution of the number of tank cars releasing per broken-rail-caused derailment by derailment speed for an 82-car train with 10 conventional, non-jacketed DOT 111A100W1 tank cars.

number of tank cars releasing of 1.83. When the speed of derailment is 40 mph, the probability of a multiple-tank-car release incident reduces to 0.32 (a 22% reduction), and the mean number of tank cars releasing reduces to 1.38 (a 25% reduction). Note that although a higher-speed track segment may have a larger number of tank cars releasing in a derailment (and may also have greater release quantities), the rate of derailment occurrence will typically be lower due to more stringent safety standards required for higher speed operations [3,19]. Addressing all of the trade-offs regarding the safety effects of train speed reduction is beyond the scope of this paper; however, it is important to consider them in the larger risk management framework in future applications of the methodology.

4.2. Enhanced tank car safety design

Tank car safety design enhancement is recognized as a risk reduction strategy [27,44,45]. A jacketed CPC-1232 compliant car has several features that reduce its likelihood of release in an accident, including a jacket, head shields and top fittings protection (Table 2). Fig. 9 compares the number of tank cars releasing if all half or all non-jacketed DOT 111A100W1 cars are replaced by jacketed CPC-1232 tank cars. If all 10 non-jacketed DOT 111A100W1 cars are replaced, the probability of a multiple-tank-car release declines from 0.41 to 0.24 (a 41% reduction), and the average number of cars releasing declines from 1.83 to 1.03, a 44% reduction.

The analysis shows that tank car safety design enhancement has a more substantial, multiplicative effect on reducing the probability of large, multiple-car release incidents (Fig. 10). For example,

Table 2
Baseline and enhanced tank car safety design.

	Conventional non-jacketed 111A100W1	Jacketed CPC-1232 compliant car
Head Thickness (in.)	0.4375	0.4375
Shell Thickness (in.)	0.4375	0.4375
Jacket	No	Yes
Head shields	None	Full Height
Top fittings protection	No	Yes
Bottom fittings	Yes	Yes
Average conditional Probability of release	0.266	0.064

Note: The CPR estimates in this table were developed assuming that all cars have tanks with a 119-inch inside diameter. The estimates were calculated assuming an “average” FRA-reportable, mainline derailment, i.e. a 26-mph derailment in which 11 cars derailed. This average derailment is based on FRA accident data for the study period. The CPR estimates also assumed that the car was in the position that had the statistically highest likelihood of release within the group of cars derailed, i.e. the 6th of the 11 cars derailed.

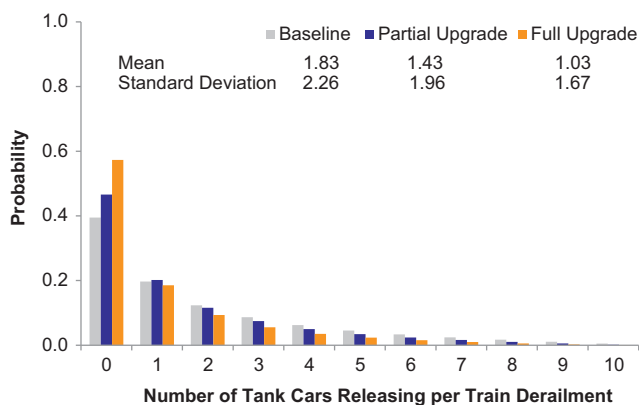


Fig. 9. Probability distribution of the number of tank cars releasing per broken-rail-caused derailment by tank car design for an 82-car train with 10 conventional, non-jacketed DOT 111A100W1 tank cars. Notes: (1) The baseline scenario is that a train contains 10 conventional, non-jacketed DOT 111A100W1 tank cars. (2) The partial upgrade scenario means that the same train carries five conventional, non-jacketed DOT 111A100W1 tank car and five jacketed CPC-1232 tank cars. (3) The full upgrade scenario means that the same train carries 10 jacketed CPC-1232 tank cars.

if all 10 conventional, non-jacketed DOT 111A100W1 tank cars are replaced by jacketed CPC-1232 cars (full upgrade scenario), the probability of a single-car-release incident is reduced by 6%. However, the same tank car upgrade strategy results in 88% reduction in the probability of a 10-car release incident. Tank car safety design enhancement reduces the occurrence of hazardous materials release incidents of all magnitudes, but the effect is more substantial for large, multiple-car release incidents.

An implicit assumption in this analysis is that the release probability of each tank car in a given accident is independent; however, this may not always obtain due to circumstance-specific factors (e.g. the interaction between tank cars and infrastructure at a particular accident location) that are not accounted for in the CPR estimation. Further research is needed to better understand the validity of the assumption of independence of different cars' CPRs in multiple-car release incidents.

Note that using more robust tank cars may reduce the tank cars' lading capacity. Consequently, this may increase the number of shipments required to meet the same traffic demand, thereby

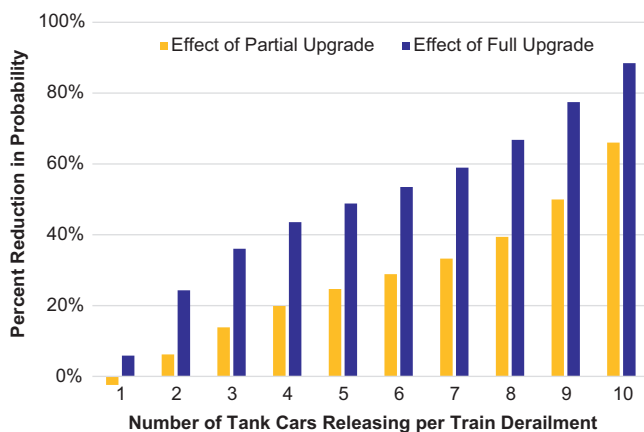


Fig. 10. Difference in probability of the number of tank cars releasing per derailment by tank car enhancement. Notes: (1) The Y axis in this figure is the percent reduction in the probability of releasing a certain number of tank cars in the partial or full upgrade scenario compared to the baseline scenario. (2) The baseline scenario is a train with 10 conventional, non-jacketed DOT 111A100W1 tank cars, compared to the partial upgrade scenario with five jacketed CPC-1232 tank cars and five conventional, non-jacketed DOT 111A100W1 tank cars, or the full upgrade scenario with 10 jacketed CPC-1232 tank cars.

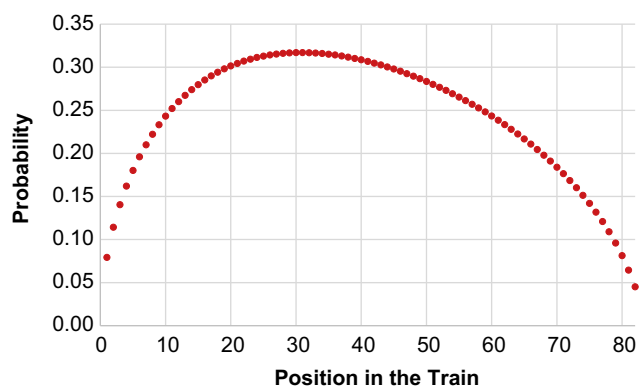


Fig. 11. Derailment profile for a broken-rail-caused train derailment for an 82-car train.

potentially increasing cars' exposure to derailments [44]; however, the enhanced safety performance of the heavier, more damage-resistant tank cars, more than offsets this effect [55].

4.3. Change of tank car position

Previous studies have suggested that tank car derailment probability is affected by its position in a train. Thus, changing tank car placement was identified as a potential risk reduction strategy [8,9,56]. In the baseline scenario, we assumed that tank cars were randomly distributed throughout the train. To understand the effect of tank car placement, we analyzed the following alternative tank car placement scenarios:

- Higher probability: tank cars are in the positions that are the most prone to derailment.
- Lower probability: tank cars are in the positions that are the least prone to derailment.

In order to estimate the number of tank cars releasing contents in different tank car placement scenarios, we developed a derailment profile, which is the conditional probability of derailment by position-in-train after a train derailment occurs [5,6] (Fig. 11). For an 82-car train derailling at 50 mph due to a broken rail, the car in the 31th position is the most likely to derail (probability = 0.317). By contrast, the last car in the train has the lowest derailment probability, 0.045.

For each tank car in the train, its derailment probability is a Bernoulli variable. As stated in Section 3.4, the sum of Bernoulli variables with different probabilities follows a Poisson binomial distribution (Appendix B). Fig. 12 compares the distributions of the number of tank cars releasing by different tank car placement scenarios. "Random" represents the baseline scenario in which tank cars are randomly distributed in the train and modeled using a multivariate hyper-geometric distribution. In the "lower probability" scenario, the probability of a multiple-tank-car release (two-or-more cars releasing) is 0.15, compared to 0.66 in the "higher probability" scenario. Overall, the mean number of tank cars releasing per derailment ranges from 0.64 to 2.27, depending on tank car placement.

Although placement of hazardous materials tank cars in portions of the train where they are less likely to be involved in a derailment appears to reduce risk, the problem is more complex. Tank car placement in trains is subject to regulatory, operational and train dynamics constraints [56–58]. There are safety trade-offs involving other segments of a car's journey from origin to destination. A comprehensive cost-benefit analysis of "optimal" tank

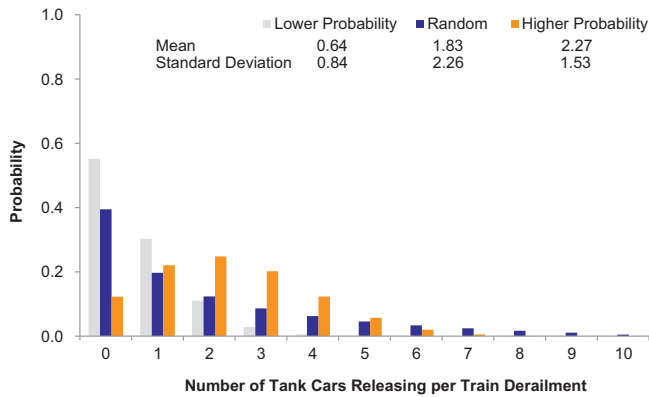


Fig. 12. Probability distribution of the number of tank cars releasing per broken-rail-caused train derailment by tank car placement for an 82-car train with 10 conventional, non-jacketed DOT 111A100W1 tank cars.

car marshaling strategy would need to account for these effects on transportation safety and efficiency.

4.4. Integrated strategies for reducing the number of tank cars releasing per derailment

In addition to analyzing the marginal effect of each strategy, it is also important to evaluate their combined safety benefit in terms of reducing the number of tank cars releasing per derailment. Table 3 shows that when all three strategies are applied, the probability of a multiple-tank-car release reduces from 0.41 (baseline scenario) to 0.02. The mean number of tank cars releasing reduces from 1.83 to 0.20.

Note that these risk reduction strategies, individually or in combination, have associated safety benefits and costs. When combined with cost information, the methodology presented here can be further developed and incorporated into a larger risk management framework to optimize the integration of multiple risk management options in the most cost-efficient manner [59].

Table 3 Safety effectiveness of integrated strategies to reduce the number of tank cars releasing per train derailment.

Scenario	Strategies		
	Speed reduction	Tank car upgrade	Tank car placement
1			
2	Y		
3		Y	
4			Y
5	Y	Y	
6	Y		Y
7		Y	Y
8	Y	Y	Y

Probability of number of tank cars releasing			
No release	Single car release	Multiple car releases	Mean number of cars releasing
0.39	0.20	0.41	1.83
0.48	0.21	0.32	1.38
0.57	0.19	0.24	1.03
0.55	0.30	0.15	0.64
0.68	0.17	0.16	0.67
0.60	0.32	0.09	0.51
0.75	0.22	0.03	0.30
0.83	0.16	0.02	0.20

Notes: (1) “Y” means that a strategy is implemented. (2) “Speed reduction” means that train speed reduces from 50 mph to 40 mph. (3) “Tank car upgrade” means that all 10 conventional, non-jacketed DOT 111A100W1 tank cars are replaced by jacketed CPC-1232 compliant cars. (4) “Tank car placement” means that all tank cars are in the positions that are the least likely to derail.

5. Conclusion

In this paper, we describe a generalized model to evaluate the probability distribution of the number of tank cars releasing in a train derailment accounting for specified operational characteristics. The analysis shows that reducing train speed, improving tank car safety design and changing tank car placement all have the potential to reduce the number of tank cars releasing per derailment. In addition, there are interactive effects among different risk reduction strategies. This analysis accounts for a variety of factors affecting the probability of a multiple-tank-car release incident. The model can contribute to development of better-informed, more effective risk management policies and practices to improve hazardous materials transportation safety.

6. Future research

This study presents one element in an ongoing systematic approach to railway hazardous materials transportation risk management. Several areas require further study:

- (1) *Consequence modeling.* Consequence modeling of hazardous materials release incidents is beyond the scope of this paper, but it is an important element of a more comprehensive approach to risk assessment. Further research is needed to better evaluate the consequences of hazardous materials release incidents, particularly large multiple car releases [60].
- (2) *Evaluate cost-efficiency of risk reduction strategies.* It is also important to evaluate the cost-effectiveness of these strategies individually and in combination. Ultimately, a decision support system will be developed to address which strategies to invest in and the optimal way to allocate resources under various conditions and circumstances.
- (3) *Other accident causes.* Further analysis is needed to account for other types of accident causes, such as mechanical failures and various human factors accident [61]. The model developed herein can be adapted to evaluate the impact of current and emerging technologies and possible safety regulations.

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Appendix A. Truncated geometric model for derailment severity

The model assumes that the number of cars derailed follows a truncated geometric distribution [5,6]

$$PN(x) = \frac{p(1 - P)^{x-1}}{1 - (1 - P)^{L_r}} \tag{A1}$$

where PN(x) represents the probability of derailing a certain number of cars (including locomotives) in a train derailment. The probability of each car derailment (P) is affected by derailment speed and residual train length (number of cars following the POD, including the POD):

$$P = \frac{e^z}{(1 + e^z)} \tag{A2}$$

$$Z = a + b \times \ln(S) + c \times \ln(L_r) \tag{A3}$$

Table A1
Parameter estimates for modeling the number of cars derailed per broken-rail-caused freight-train derailment, Class I mainlines, 2002 to 2011.

Parameter	Estimate	Standard Error	95% Confidence Interval
<i>a</i> (intercept)	1.2153	0.3762	0.4761
<i>b</i> (speed)	−1.2064	0.0689	−1.3417
<i>c</i> (residual train length)	0.0039	0.0856	−0.1643
<i>d</i> (loading status of POD)	−0.3124	0.0668	−0.4436

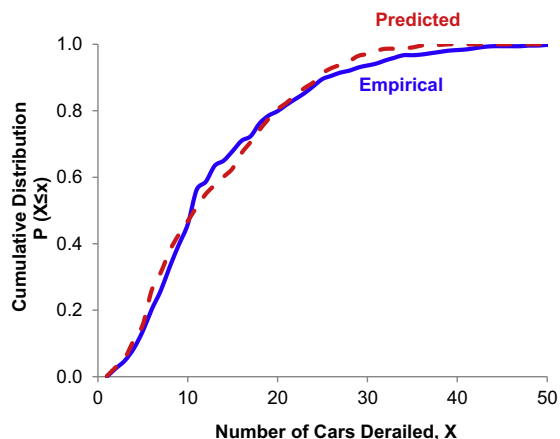


Fig. A1. Comparison of empirical and predicted train derailment severity distributions, broken-rail-caused Class I railroad freight-train mainline derailments, 2002 to 2011.

The mean number of cars derailed per derailment is:

$$E(x) = \sum_{x=1}^{L_r} PN(x)x = \frac{1}{P} - \frac{L_r(1-P)^{L_r}}{1-(1-P)^{L_r}} \quad (\text{A4})$$

where $PN(x)$ = probability of derailling a certain number of cars in a train derailment; x is the number of cars derailed; $L_r = L - \text{POD} + 1$ is the residual train length (number of cars following the POD); L is the train length (total number of cars in a train); S is the derailment speed (mph); a , b , c are the parameter estimates (dependent on accident cause).

In addition to the two variables (speed and residual train length) considered in previous studies, we considered a new factor—loading status of the first car derailed. The loading status of POD (variable name L_d) was treated as a dummy variable (loading = 1 represents a loaded POD, empty otherwise). Parameter coefficients were estimated using a nonlinear regression on the mean number of cars derailed [24]. Table A1 presents the parameter estimates for modeling broken-rail-caused number of cars derailed.

Fig. A1 compares the empirical and predicted distributions of train derailment severity. The Kolmogorov–Smirnov (K–S) test shows that the two distributions are statistically identical ($K_{sa} = 0.93$; $P = 0.35$). It indicates that the truncated geometric model has a reasonable fit for modeling broken-rail-caused train derailment severity.

Appendix B.

Tank car derailment probability by position-in-train

We used the worst-case placement scenarios of five conventional non-jacketed DOT 111A100W1 tank cars as an example. The conditional derailment probability of these cars are 0.29295, 0.29284, 0.29283, 0.29252 and 0.29250, respectively (Fig. 11). The derailment probability of each car in a specific train position is a Bernoulli variable. The sum of Bernoulli variables with heterogeneous probabilities follows a Poisson binomial distribution [47]. Therefore, the probability of derailling a certain number of DOT

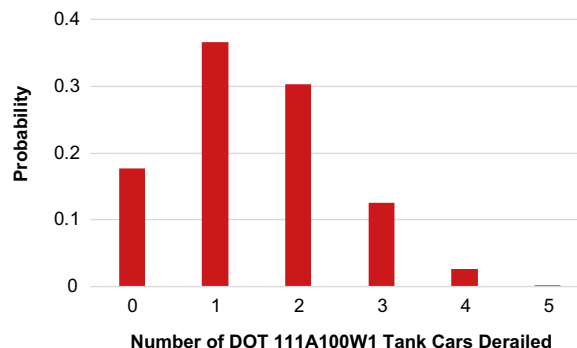


Fig. B1. Probability distribution of the number of DOT 111A100W1 tank cars derailed per train derailment.

111A100W1 tank car is calculated using the algorithm implemented in statistical software R [52] (Fig. B1).

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