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Abstract
Recent changes in freight train operating practices call for improved understanding of the effect of hazmat car placement on hazmat release risk. In existing models, placement of hazmat cars in a train is either assumed to be random or in blocks of grouped cars. There has been little investigation of how different train configurations affect the number of hazmat cars that could potentially derail in an accident. This paper presents a probabilistic model that calculates the probability and number of hazmat cars derailed based on accident characteristics and train configuration. The model distinguishes between hazmat and non-hazmat cars in manifest trains and provides probability distributions and the expected number of hazmat cars derailed under a set of train placement scenarios. The results indicated that the number and distribution of hazmat cars derailed were affected by speed, percentage of hazmat cars in the train (given the same train length), train configuration, and number of hazmat cars in the train (given the same percentage of hazmat cars in the train). The model presented here could be used as a stand-alone tool to evaluate train-configuration-based hazmat car derailment risk, as well as an integral component of an enhanced, comprehensive rail hazmat transportation risk analysis framework. The model results could be used to answer questions in hazmat transportation risk assessment, rail shipment planning and optimization, and tradeoffs related to unit train versus manifest train operation. The results could also inform potential policies about hazmat car placement in trains and operating speed.

Keywords
freight systems, hazardous, rail, train, safety, safety performance and analysis, modeling and forecasting

Over 2 million carloads of hazardous materials (hazmat) are shipped by rail in the United States each year (1). Nearly all of these shipments arrive at their destination without incident (2). Nevertheless, railroad releases of hazardous materials have the potential for catastrophic consequences. Consequently, efforts to manage and further reduce risk are ongoing.

Hazmat cars can be transported individually or in small groups (aka “cuts”) of cars coupled together as part of manifest trains. Such trains consist of different types and numbers of railcars carrying both regulated and non-regulated materials traveling between various different origins and destinations that have been grouped into a single train during a portion of their journey. It is not uncommon for dozens of hazmat cars to be transported together in a manifest train. If there is enough traffic between the same origin and destination, hazmat cars may also be transported in unit trains in which the entire trainload is the same commodity. Although hazmat unit train traffic, especially flammable liquids, has increased considerably over the last decade and a half, the majority of hazmat traffic continues to be transported in manifest trains (3).

Recent changes in freight train operating practices suggested the need for a better understanding of how placement of hazmat cars in a train affects the likelihood

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and number of hazmat cars that might be involved if a train derails. For example, precision scheduled railroading (PSR), an efficiency-oriented rail operational strategy, has altered most major North American railroads’ operating strategies. The objective is to run fewer, longer trains thereby reducing operating costs and railcar transit time, and at the same time improving railcar and locomotive utilization (4). Given a fixed amount of traffic, operating fewer, longer trains may also reduce the overall derailment rate owing to the reduced exposure to derailment causes related to train miles; however, it may increase the probability of an individual train derailing (5). When a longer train derails, there is a greater chance that more railcars will derail (6). This increases both the likelihood of a hazmat car derailing and the potential for a release from one of these cars (7). Previous research has also shown that, ceteris paribus, the conditional probability of release (CPR) of tank cars involved in the derailment is positively correlated with the severity of the derailment (8) (severity is defined here to mean the number of cars derailed in a given derailment). Placement of hazmat cars in a train can also affect their likelihood of being involved in a derailment (9–11).

Literature Review

Considerable research has focused on railroad tank car release risk because tank cars account for over 70% of rail hazmat shipments (1). These studies include improving hazmat packaging and tank car design (12, 13), upgrading railroad infrastructure (14, 15), and optimized routing (16–18). Li et al. found that certain characteristics of manifest and unit train derailments differed, such as the number of cars involved and the distribution of accident causes (19). Some integrated risk models have been developed to address multiple aspects of rail hazmat release risks (14, 20–22). Saccomanno and El-Hage used an empirical analysis of train derailment data to investigate the effect of train makeup on hazmat release risk (23, 24). Their position-dependent distribution of derailment probability of railcars in a train has been used by other researchers to assess position-dependent tank car derailment probability (10, 25–28). Hosseini and Verma used a conditional value-at-risk methodology to optimize train configurations and routing of rail hazmat shipments (29). All of these studies addressed derailment probability of tank cars based on their position in a train; however, the relationship between railcar placement in trains and derailment severity is not fully understood. Previous models either assumed random placement of cars in a train, or placement in blocks in which all cars are grouped together (11, 25, 30, 31). The authors are unaware of any previous study that has examined the precise relationship between detailed train configuration and the number of hazmat cars that derail.

Following investigation of two severe flammable liquid train derailments, the National Transportation Safety Board (NTSB) issued a Safety Recommendation Report that recommended that railroads consider systematic placement of the most vulnerable tank cars in high-hazard flammable trains to reduce hazmat release risk (32). The report discussed the effect of hazmat car placement, considering both their position in the train and the type of tank car, on release risk. Different types of tank cars vary in their resistance to damage when involved in derailments (8). The NTSB report also pointed out that the type of railcars adjacent to a tank car might affect the impact characteristics experienced by a nearby tank car. Additionally, NTSB suggested that adjacent cars might affect the derailment probability of hazmat cars.

A review of the literature found that there has been a focus on research to reduce hazmat release risk by consideration of various railcar placement strategies, consistent with the NTSB report (32). Understanding how many hazmat cars would be derailed is a critical input to calculating the risk of multiple hazmat car release incidents. Related to this is the need to understand the factors affecting hazmat car derailment severity with various train makeup configurations.

Research Objectives

This paper presents a probabilistic model that calculates hazmat car derailment likelihood and severity based on accident characteristics and train configuration. The model distinguishes between the derailment probability of hazmat and non-hazmat cars and provides a probability distribution of the number of hazmat cars expected to derail under various railcar placement scenarios. The model is illustrated using a case study of manifest trains configured in various ways, and includes sensitivity analyses investigating how derailment speed, train length, and percentage of hazmat cars in the train affect the number of hazmat cars derailed. The model could be used as a stand-alone tool to evaluate train-configuration-based hazmat car derailment risk, and as part of an integrated railroad hazmat transportation risk analysis framework.

Hazmat Car Train Placement Model

A simple example is presented for illustrative purposes (Figure 1). Consider a train consisting of seven total vehicles (two locomotives and five railcars). Two of the latter are hazmat tank cars in Positions 4 and 6 (Figure 1a).
When the train derails, there are three possible outcomes for the two hazmat tank cars:

1. One of the two hazmat tank cars derails,
2. Both hazmat tank cars derail, or
3. Neither of the hazmat tank cars derail.

Let the result of the derailment be denoted as $T(a, b)$ where “a” is a nonzero positive integer for the position in the train indicating the first derailed vehicle (FDV) and “b” is a nonzero positive integer indicating the total number of vehicles (cars and locomotives) derailed (VDR). For example, $T(2, 5)$ signifies five total vehicles derailed (VDR = 5) where the first derailed vehicle is the second locomotive (FDV = 2) (Figure 1b). It was assumed that there is only one FDV per derailed train, which covers a substantial majority of train derailment scenarios. Since every result, $T$, is mutually exclusive (i.e., it is not possible to simultaneously have a two-car derailment and a three-car derailment given the same FDV), assuming a derailment only takes place once and at one location in a train, then the sum of the probabilities of $T(a, b)$, meaning the sum of the probabilities of all possible results, given the derailment event, $D$, occurs, is one, that is,

$$\sum P(T(a, b)|D) = 1 \tag{1}$$

Next, let NHD be the number of hazmat cars derailed. The probability of a specific number of hazmat cars derailed can be calculated by adding up the probabilities of all the derailment results that cause that number of hazmat cars derailed. Therefore, the probability of $x$ hazmat cars derailed is,

$$P(NHD = x) = \sum P(NHD = x|T(a, b)) \tag{2}$$

For example, the derailment scenario $T(1, 4)$ (Figure 1c) would result in one hazmat car derailed, because the FDV is one (the first locomotive) and there are four cars derailed including the hazmat car at the fourth position. Therefore its probability should be considered in $P(NHD = 1)$. On the other hand, the derailment scenario $T(1, 6)$ (Figure 1d) would include both hazmat cars, and its probability should be considered in $P(NHD = 2)$. The probability of one hazmat car derailed can be calculated as follows:

$$P(NHD = 1) = P(T(1, 4)) + P(T(1, 5)) + P(T(2, 3)) + P(T(2, 4)) + P(T(3, 2)) + P(T(3, 3)) + P(T(4, 1)) + P(T(4, 2)) + P(T(5, 2)) + P(T(5, 3)) + P(T(6, 1)) + P(T(6, 2))$$

Likewise, the probability of two hazmat cars derailed is,

$$P(NHD = 2) = P(T(1, 6)) + P(T(1, 7)) + P(T(2, 5)) + P(T(2, 6)) + P(T(3, 4)) + P(T(3, 5)) + P(T(4, 3)) + P(T(4, 4))$$

The calculation of $P(T(a, b))$ uses two probabilistic models. The first is the probability distribution of the normalized first derailed vehicle (NFDV), which is the ratio of FDV to the total train length, representing the relative positioning of the FDV. Using the United States Department of Transportation Federal Railroad Administration (FRA) empirical train accident data from 2002 to 2011, a beta distribution (0.6793, 0.8999; Kolmogorov–Smirnov test) provided the best fit for the NFDV. The derived distribution is based on data with all derailment causes combined, but analogous distributions could be developed using the derailment-cause-specific NFDV distributions (33). Given a total train length, $L$, the probability that the FDV is at the $k$th position, $FDV(k)$, was estimated using Equation 3,

$$P(FDV(k)) = F\left(\frac{k}{L}\right) - F\left(\frac{k-1}{L}\right) \tag{3}$$

where

$P(FDV(k))$ = the probability that FDV is at the $k$th position of a train,

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

$L$ = train length (total number of locomotives and railcars).

The second model is the probability distribution of the number of locomotives or railcars derailed, representing total derailment severity. Train derailment severity is affected by derailment speed, FDV, train length, loading
status of railcars, and other factors. The statistical model for estimating train derailment severity given FDV was developed by Saccomanno and El-Hage (23, 24) and was updated by Liu using the FRA train derailment data from 2002 to 2011 (10). The probability distribution of the total number of cars derailed given that the FDV at the kth position of the train is estimated as:

\[
P(x|k) = \frac{\exp(Z)}{1 - \frac{1}{1 + \exp(Z)}}
\]

where

\[
Z = a + b \times \ln(V) + c \times \ln(LR) + d \times LO(FDV)
\]

1. Front: All hazmat cars placed in front of the other railcars in the train;
2. Back: All hazmat cars placed at the back of the train;
3. Mid-train: All hazmat cars placed at the middle of the train;
4. Front & back: The hazmat cars divided into two groups with approximately half at the front and half at the back of the train (17 and 18 cars, respectively); and
5. Random: The hazmat cars were randomly and independently distributed among the other railcars in the train.

For the random distribution case, a hypergeometric probability distribution was used to characterize hazmat car placement in the train as suggested by Liu et al. (25) and Glickman et al. (34). The probability distribution of hazmat car derailment severity and the expected number of hazmat cars derailed for each train configuration were calculated under two derailment speeds: 25 and 50 mph.

The model was used to develop the probability distribution of the number of hazmat cars derailed (severity) for each of the five train configurations at 25 and 50 mph (Figure 3). The x-axis shows the number of hazmat cars derailed, and the y-axis the probability that more than zero, that is, at least one hazmat car derailed. Thus at 25 mph, the probability of having at least one hazmat car derailed in the “Back” scenario was 0.4 and the probability for the “Random” scenario was 0.87 (Figure 3a). The probability of more than five hazmat cars derailed in the Back scenario at 25 mph was about 0.22 (Figure 3a) whereas the probability of at least five cars derailing in this scenario at 50 mph was 0.32 (Figure 3b).

**Effect of Hazmat Car Placement on Number of Hazmat Cars Derailed**

At 25 mph, the “Front” and “Mid-train” scenarios had the highest probability of derailing more hazmat cars than other scenarios. At 50 mph, the Mid-train scenario had the highest probability of derailing the most hazmat cars, followed by the Front scenario. This is because at higher speeds, the position-dependent probability of railcar derailment is concentrated in the middle of the train (6, 33). The “Front & back” scenario had the lowest probability of derailing a large number of hazmat cars, especially numbers exceeding half the total number of hazmat cars in the train. This is because only the very largest derailments will involve both the front and back sections of the train (Figure 2).

Consistent with previous research on the effect of speed on derailment severity, all scenarios had higher
probabilities of larger numbers of hazmat cars derailed at 50 mph compared with 25 mph. At both derailment speeds, the probability distributions for the four other placement scenarios differed from the Random scenario that has been assumed in some prior studies. Compared with the other scenarios, the Random scenario resulted in higher probabilities of a lower number of hazmat cars derailed, and lower probabilities of a large number of hazmat cars derailed.

**Expected Number of Hazmat Cars Derailed**

The expected number of hazmat cars derailed was calculated for each of the five scenarios at 25 and 50 mph (Figure 4). At 25 mph, the Front scenario resulted in the highest expected number of hazmat cars derailed, followed by Mid-train, Random, Front & back, and Back. At 50 mph, the Mid-train scenario had the highest expected number of hazmat cars derailed, followed by the Front, Random, Back, and Front & back scenarios. The differences in the expected number of hazmat cars derailed among the five scenarios was also greater at 50 than 25 mph. For example, at 25 mph, the difference between the scenario with the highest expected number of hazmat cars derailed (Front, 5.69), and the scenario with the lowest (Back, 3.74), was 1.95. This difference increased to 4.01 at 50 mph where the scenario with the highest expected number of hazmat cars derailed was Mid-train (9.24) and the scenario with the lowest was Front & back (5.23). This suggests that derailment speed not only affects FDV and total derailment severity, but also position-dependent hazmat car derailment severity.

Placement of hazmat cars randomly throughout the train is more realistic in relation to current operational
practice for train makeup. Positioning them all in the back, or partially in the front and back, resulted in estimates of fewer average hazmat cars derailed. Nevertheless, although placement of hazmat cars in these locations in a train has the potential to reduce the number of hazmat cars derailed in mainline derailments, a more holistic approach should be taken. Achieving the aforementioned train configurations would, in general, require additional switching moves while building trains in classification yards. These additional moves raise two potential problems: they increase exposure to derailments and collisions resulting from human error or component failure in yards (32), and they increase the time required in yards thereby reducing operational efficiency. The results presented here could be used as part of an evaluation of the risk tradeoff between optimal hazmat car placement strategies, and the increase in risk and efficiency costs introduced by the additional activities in classification yards needed to achieve such strategies (35).

In the following subsections, several sensitivity analyses are presented to further understand the effect of train derailment speed, number of hazmat cars in a train given the same percentage of hazmat cars in the train, and the percentage of hazmat cars in a train given the same total number of rail vehicles in the train, on the distribution of the number of hazmat cars derailed.

**Sensitivity Analysis 1—Effect of Train Derailment Speed**

To further understand the effect of derailment speed on the expected number of derailed hazmat cars, a sensitivity analysis was conducted in which derailment speed was varied for the case-study train (Figure 5). As expected, the number of hazmat cars derailed increased with speed for all scenarios, but which scenario resulted in the largest expected number of cars derailed varied. At low derailment speeds, the Front scenario had the highest expected number of hazmat cars derailed, but when the speed exceeded 25 mph the Mid-train scenario had the highest. Conversely, at low speeds, the Back scenario had the lowest expected number of hazmat cars derailed, but at speeds greater than 31 mph the Front & back scenario had the lowest. These results indicate that the effectiveness of hazmat car placement strategies intended to minimize hazmat derailment severity will vary depending on the speed of the train when it derails.

**Sensitivity Analysis 2—Effect of Train Length**

The results described above were based on the case-study train with four locomotives, 71 non-hazmat cars, and 35 hazmat cars. Different train configurations, that is, different total train length and percentage of hazmat cars in the train, may affect which hazmat car placement scenarios result in the lowest and highest expected numbers of hazmat cars derailed. Consequently, we conducted a sensitivity analysis to investigate the effect of train length. Train length was varied while maintaining the same percentage (31.8%) of hazmat cars in the consist (35 out of 110) as used in the case study. This was done by adding or subtracting the corresponding number of hazmat cars for different train lengths. For example, in a train with a consist length of 130 (locomotives and railcars) the number of hazmat cars was increased to 43, whereas for a consist length of 90 the number was reduced to 29 hazmat cars. The model was then run to determine the expected number of hazmat cars derailed for each of the five scenarios (Figure 6). The result showed that for a given train speed and percentage of hazmat cars in a train, changing the total train length did not affect the order of the expected number of hazmat cars derailed among the different scenarios. Under this setting (25 mph and 31.8% hazmat cars in a train), placing all the hazmat cars Mid-train consistently resulted in the highest expected number of hazmat cars derailed, followed by the Front, Random, Back, and Front & back scenarios.

**Sensitivity Analysis 3—Effect of Percentage of Hazmat Cars in a Train**

Also of interest is how the expected number of hazmat cars derailed might be affected by the percentage of hazmat cars in a train consist, so a sensitivity analysis was conducted to investigate this. The same five hazmat car train placement scenarios were analyzed but with differing numbers of hazmat cars in the consist (Figure 7). Total consist length was held constant at 110 but the makeup of the train was varied to include, 15, 35, 55,
and 75 (13.6%, 31.8%, 50.0%, and 68.2%, respectively) hazmat cars. Not surprisingly, the expected number of hazmat cars derailed increased with their percentage in the train. Larger percentages of hazmat cars in the train reduced the relative difference in expected number of hazmat cars derailed among the five scenarios. In other words, when the percentage of hazmat cars was high, the effect of their placement on severity was reduced. This effect was more evident at 25 than at 50 mph, indicating that different hazmat car placement strategies had a greater impact on higher speed derailments.

Figure 5. Effect of derailment speed on the expected number of hazmat cars derailed for the five hazmat car train placement scenarios.

Figure 6. Effect of train length on the expected number of hazmat cars derailed for the five hazmat car train placement scenarios (31.8% hazmat cars in the consist and a derailment speed of 25 mph).

Figure 7. Effect of different percentages of hazmat cars in the consist on the expected number of hazmat cars derailing in 25 and 50 mph derailments for the five placement scenarios involving (a) 15, (b) 35, (c) 55, and (d) 75 hazmat cars.
Conclusions and Future Research

A probabilistic method was developed to assess hazmat car derailment severity under different derailment characteristics, hazmat car placement strategies, and train configurations. Derailment speed, train length, hazmat car placement, and number of hazmat cars in the train, all affected hazmat car derailment severity. This model enables evaluation and comparison of hazmat transportation risk for different types of rail operations. For example, the risk of transporting the same number of hazmat shipments via unit trains (fewer trains but with more hazmat cars per train) compared with manifest trains (more trains with fewer hazmat cars per train) could be compared considering various placement strategies. By providing more accurate and detailed hazmat car derailment severity assessment based on hazmat car placement, a more sophisticated and comprehensive, network-level rail hazmat transportation risk analysis could be carried out by considering both mainline and yard hazmat car derailment risk, both of which are affected by car placement strategies. In the unit train versus manifest train comparison, unit train operation requires fewer yard switching moves compared with manifest trains and therefore is less prone to yard accidents and release risk. The tradeoff is that if a unit train derails on a mainline, it is more likely to result in more hazmat cars derailed compared with a manifest train, leading to higher chances of a release and greater quantities spilled. Using the model presented here, different placement strategies could be considered for various manifest train configurations and their risks compared with unit train operation, or among different manifest train operations to identify strategies to most effectively manage the risk.

Another application of this model is to assess the potential change of hazmat transportation risk as a result of new operating practices such as PSR. One of its operating strategies is running fewer but longer trains to enhance efficiency. Train makeup, hazmat car assignment, and yard operating strategies will also change, potentially affecting hazmat transportation risk. These risks could be more accurately assessed using the probabilistic model developed in this research thereby contributing to better-informed, risk-based decision making and planning under PSR.

The general hazmat car placement model presented in this study supports the development of a more sophisticated and refined rail hazmat transportation risk assessment framework that will include hazmat train derailment probability, derailment severity, CPR, and release consequences, and account for various affecting factors. It could also be integrated into existing hazmat risk models such as the multiple tank car release model (25, 31) to improve the accuracy and practicality of risk estimates.

Model Limitations and Future Research

Some assumptions and limitations of the model developed in this research and corresponding future research opportunities are summarized as follows:

1. This research focused on assessing the probability of hazmat car derailment severity without considering the loaded or empty status of railcars in the train. The corresponding four- to fivefold difference in weight affects train dynamics, which in turn affects the stability of the train and potential for a derailment (37, 38). Incorporating the loaded status of cars in the train and their effect on the model described here should be addressed in future research.

2. This research focused on probability estimates of hazmat car derailment severity in a given train accident. Recent studies of freight train derailment rates (39, 40) could be combined with the derailment severity model to derive hazmat car derailment risk under various train configurations. This could be integrated into a comprehensive, network-level hazmat car derailment risk assessment framework.

3. This study did not attempt to account for the derailment probability of different types of railcars. As mentioned in the Literature Review section, different types of railcars have different structural designs and operational dynamics that may affect corresponding failure mechanisms (32). Future research and development of the model presented here should consider the potential effect of derailment probabilities for different railcar types.

4. The model assumes that a derailment only occurs at one location in a train. In rare instances, a train may derail at multiple locations within a train or have a secondary derailment that is caused by the first derailment. Future research could address the risks of multiple-location or multiple-occurrence derailments.

5. This model focused on deriving hazmat car derailment severity and did not consider any network effect that different hazmat car placement strategies would bring. Future research could use the general hazmat car placement model developed in this study to analyze the effect of hazmat car placement on hazmat release risk, consequence analysis, and comparison of unit train-versus manifest train risk and efficiency.
Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: C.-Y. Lin, J. Kim, C. P. L. Barkan; data collection: C.-Y. Lin, C. P. L. Barkan; analysis and interpretation of results: C.-Y. Lin, X. Liu, J. Kim, C. P. L. Barkan; draft manuscript preparation: C.-Y. Lin, X. Liu, C. P. L. Barkan. All authors reviewed the results and approved the final version of the manuscript.

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