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Quantifying the Influence of Tank Car Position and Train Configuration on the Risk of Rail Transport of Class 3 Flammable Liquids

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Abstract

As the amount of high-hazardous materials (hazmat) being shipped in high-hazard flammable unit trains (HHFUT) increases, mitigating the risks associated with railway transportation of hazmat remains an industry priority. Compared with HHFUT configurations, the placement of hazmat railcars in high-hazard flammable trains (HHFT) and the number of classification yards they traverse can affect the risk of derailment and subsequent hazmat release for HHFTs. This paper evaluates hazmat release risks associated with the transportation of U.S. Department of Transportation (U.S. DOT) Class 3 flammable liquids by tank cars. Specifically, it compares the risks of HHFUTs and HHFTs for shipping a designated amount of hazmat and considers both mainline and yard operations in alignment with existing regulations and practical guidance. The methodology quantifies the transportation risk in total expected release consequence (i.e., casualties) given the total amount of Class 3 flammable liquids transported in HHFUT and HHFT configurations with different tank car placement strategies. Based on the case study, we find that using five 100-railcar HHFTs, each with 20 tank cars in positions 66 through 85, is both practical and generates the lowest transportation risk. Some hazmat railcar placement strategies in HHFTs lead to a higher release risk than HHFUT operations, while others result in a lower release risk. The proposed methodology could be extended to diverse operating scenarios to better understand the impacts of train configuration and tank car placement on the risk of rail transport for flammable liquids.

Keywords

freight systems, transportation of hazardous materials, rail, freight rail transportation

In 2021, United States (U.S.) Class I railroads transported about 2.2 million carloads and 180 million tons of chemicals (*1*). In this context, 103,312 tank cars were specifically designated for transporting DOT Class 3 flammable liquids (*2*). Among these, approximately 13% were allocated for the transportation of petroleum crude oil. Given their inherent combustibility, these liquids are transported in specially designed railcars and containers that adhere to stringent regulations to prevent leaks and spills. Although rail transportation has long been considered the safest way to move large quantities of hazardous materials (hazmat) over long distances in the U.S., accidents do still happen, and their potentially severe consequences remain a significant concern in the rail and hazmat industries (*3*, *4*).

Most rail hazmat shipments involve more than one train movement because of the long distances traveled and the need to move railcars between sidings, branch

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lines, and major mainline routes that may be owned by different rail carriers (*5*). Rail hazmat shipments are commonly transported by manifest trains and unit trains. Typically, manifest trains carrying hazmat and other non-regulated ladings pass through railroad yards and individual railcars may be switched between trains during each trip. Recently, there has been a trend of transporting hazmat via dedicated unit trains, which carry a single type of commodity (flammable liquids, for example, as shown in this paper), continuously moving from one origin to one destination (*6*). If the total amount of hazmat being transported remains constant, the same number of railcars are required to ship it, but more manifest trains than unit train shipments are needed to transport these cars. Assuming that the total amount of hazmat is fixed, the trade-off in risk between unit trains and manifest trains stems from the trade-off between the potentially higher likelihood of train derailment if hazmat is transported by manifest trains (because more trains are used and additional yard operations are required) and the potentially more severe consequences of a release in a unit-hazmat-train derailment (because a unit train can carry more tank cars than a manifest train).

The most recognized risks of rail transportation often occur on mainlines, in classification yards and terminals, or in the neighborhoods adjacent to or nearby classification yards and terminals (*7*). There are generally two types of risk for unit train shipments: a unit train experiences risk on mainlines during line-haul events and when it arrives at or departs from terminals during arrival/departure (A/D) events. In addition to risks related to line-haul events on mainlines and A/D events in yards, a manifest train encounters further risks from switching and sorting in the classification yards during yard-switching events (*8*, *9*).

Given this paper's specific focus on Class 3 flammable liquids, as defined by Federal Regulation 49 CFR § 171.8, the terms high-hazard flammable trains (HHFT) and high-hazard flammable unit trains (HHFUT) are used. HHFTs are characterized by carrying 20 or more cars loaded with Class 3 flammable liquids in a contiguous block or 35 or more such cars throughout the entire train, whereas HHFUTs involve transporting 70 or more cars loaded with Class 3 flammable liquids. The aim of this paper is to compare the risks associated with using HHFUTs versus HHFTs to transport a certain quantity of Class 3 flammable liquids. For HHFTs, our focus is on trains transporting Class 3 flammable liquids in a continuous block, representing an extreme scenario where derailment and hazmat release could have significant consequences, especially since most derailments occur in subsequent cars. Consequently, HHFTs with 35 or more tank cars distributed across the train are not discussed in detail. However, this exclusion does not detract from the paper's scope, which remains centered on comparing the risks of HHFUTs and HHFTs transporting hazardous materials. Given the complexity of hazmat segregation and the multifaceted considerations involved in incorporating buffer cars for trains transporting multiple types of hazardous material, this paper focuses exclusively on a single type of hazmat. This decision ensures that our model remains manageable, allowing for more refined and accurate analysis within its defined parameters.

Existing research (*7*, *9–12*) on rail transportation of DOT Class 3 flammable liquids highlights that tank car placement affects the expected consequences of a potential train derailment because of the position-dependent derailment probability for each car. Kang et al. (*9*) proposed a novel event-chain-based risk assessment methodology, detailing the complete calculation steps for quantifying the risks of rail transport of DOT Class 3 flammable liquids considering both mainline and yard/terminal train operations. This method compares risks between HHFUTs and HHFTs by distinguishing influencing factors such as derailment rates for HHFUTs and HHFTs, classification yard type, tank car placement on the HHFT, and yard-switching approach.

Kang et al. (*9*) conducted a case study comparing different hazmat transportation service options using one HHFUT or five HHFTs to transport 100 tank cars over 400 mi. The hazmat type studied in their paper was DOT Class 3 flammable liquids, which is the same category of hazmat considered in this paper. In their study, each HHFT consisted of five locomotives, 20 tank cars (carrying the same hazmat), and 80 non-hazmat rail cars. In comparison, an HHFUT included five locomotives and 100 tank cars. Their results found that placing tank cars at the end of an HHFT (positions with the lowest probability of derailing) could reduce the possible releasing consequences to some extent. The service option that includes multiple (five) HHFTs and places tank cars at the end of HHFTs might encounter smaller risks compared with the service option where all tank cars are in one HHFUT. The inverse conclusion follows when the block of 20 tank cars is placed at positions with the highest probability of derailing in HHFTs. A limitation of Kang et al. (*9*) is that they designed the train consists only from the perspective of derailment probability without considering safety concerns for crew members on locomotives or occupied cabooses. The National Transportation Safety Board (NTSB) has published a safety recommendation (*13*) stating that if train length allows, a tank car must be placed no closer than the sixth car away from the locomotive; or, if the train length does not allow for a five-car buffer, trains may include a single buffer car. However, this recommendation has not yet been formalized into a regulation.

While the risk of a loaded tank car derailing may be lowest when positioned at the tail-end, if there is too much tonnage in the rear portion of the train, then overall train stability is compromised. Most railroads restrict the overall percentage of the total train tonnage permitted in the rear of the train. Therefore, the scenarios considered by Kang et al. (*9*) may not be the most practical for HHFTs with many empty railcars. In addition, the train consists on mainlines and during A/D at terminals in Kang et al. (*9*) are constructed according to position-dependent derailment probabilities on mainlines. However, the positions with the lowest probability of derailing on mainlines do not represent the train positions with the lowest probability of derailing when considering the sum of line-haul and A/D risks. These limitations lead to the need for a more comprehensive case study to investigate the transportation risks related to more possible tank car positions.

The main contribution of this paper is to explore practical train arrangements for circumstances when the "best-case HHFT consist" discussed in Kang et al. (*9*) is not supported by the engineering sense of "best practice." We design service options with relatively random tank car placements to investigate the different expected consequences between service options with various train configurations and tank car positions. Similar to Kang et al. (*9*), this paper conducts a case study to demonstrate the refined risk assessment of transporting DOT Class 3 flammable liquids by rail. This paper encompasses various tank car types, including commonly used models such as DOT-117 and DOT-111, designed for the transportation of DOT Class 3 flammable liquids. To streamline the comprehensive risk assessment model, this paper considers only one type of hazmat in each train. In addition, Kang et al. (*9*) assumed that the occurrence of the release incident always leads to a fire event, which is unrealistically conservative. This paper replaces this assumption with a more detailed estimation of the conditional probability of a fire event given a release. More details will be provided in the designed scenarios section.

The remainder of this paper is organized as follows. The literature review section reviews previous work. The methodology section details the improvements we made based on previous work. The risk calculation section provides details of the case study and shows the differences between using HHFUTs and HHFTs with various tank car placement strategies. Subsequently, the impact of train length on the expected risks is investigated. The following research limitations section discusses the limitations of this paper and the assumptions made. Further insights and limitations are discussed in the conclusion section.

Literature Review

The event chain of a hazmat release incident involves multiple risk components, whether on mainlines or in yards and terminals. Generally, a release incident of a tank car carrying DOT Class 3 flammable liquids consists of the following event chain: 1) a train derailment occurs during train operations; 2) one or more railcars derail in this incident; 3) the derailed railcars involve at least one tank car; 4) at least one derailed tank car releases its content; and 5) the released content ignites and results in various types of consequence. To analyze the risk of a train derailment involving hazmat release, the following elements have been studied in previous papers: the likelihood of a train derailment on a track segment (*14–17*); the number of railcars derailed (*18–21*); the number of tank cars derailed (*22–25*); the number of tank cars releasing contents (*23*, *26–28*); and the derailment consequences (*25*, *29–31*).

Some prior risk analysis studies have explored multiple risk components of the event chain. For example, Liu et al. (*32*) calculated the probability of a release incident given a train derailment. Bagheri et al. (*22*) used a truncated geometric model to estimate the number of cars derailing and then multiplied the conditional probability of release to estimate the number of tank cars derailing and releasing. However, they did not consider different train configurations (especially HHFTs), or the probability distribution of the amount released. Liu (*10*) improved the model that Bagheri et al. (*22*) developed by considering different derailing probabilities at different train positions. Liu (*10*) focused on probability analysis of a release incident without accounting for the number of tank cars releasing contents or the consequences. Prabhakaran and Booth (*33*) simulated multiple scenarios of tank car puncture and subsequent content release. Bing et al. (*34*) calculated the derailment frequency and conditional probability of a car derailment after a train accident occurs. Liu et al. (*27*) calculated the probability distribution of the number of cars derailed and the number of tank cars releasing contents. They did not account for derailment probability differences by train position. Lin et al. (*35*) evaluated the impacts of tank car placement on the likelihood and severity of derailment, but they did not develop a consequence model. Since the derailment of a train accident may not involve tank cars (especially for HHFTs), it is critical to estimate derailment or release probability at each train position when studying the transportation risk concerning train configurations and the placement of tank cars.

Previous studies statistically investigated the relationship between tank car placement and derailment risk. The NTSB (*36*) states that railcars positioned at the rear end of a train tend to have a lower probability of derailment and release probability. In addition, Anderson and Barkan (*37*) did a statistical analysis and found that positions at the rear end of a train have a lower frequency of derailment. By analyzing 5,451 train derailments that occurred from 1982 to 1985, the U.S. Department of Transportation (U.S. DOT) Federal Railroad Administration (FRA) (*7*) found that the last quarter of a train had a lower derailment risk. However, they did not quantitatively model the risk of derailment and hazmat release.

More recent work has built the foundation for this paper. Zhao and Dick (*38*) and Zhao et al. (*39*) explored the derailment likelihood associated with A/D and yard-switching operations for unit and HHFTs using historical derailment data from 1996 to 2018. Zhang et al. (*40*) performed a similar analysis for mainline operations using derailment data from the same period. Based on Zhao and Dick (*38*), Zhao et al. (*39*), and Zhang et al. (*40*), Kang et al. (*9*) developed a comprehensive risk analysis considering both mainline and yard operations. This paper improves Kang et al. (*9*) by proposing a more sophisticated model that considers the proportion of release events that involve combustion.

Designed Scenarios

Compared with Kang et al. (*9*), a similar case study setting was implemented to demonstrate the practical enhancement of the risk assessment model presented in this paper. We assume that 100 tank cars (transporting Class 3 flammable liquids) conforming to DOT-117 tank car specifications need to be transported 400 mi (the use of DOT-117 is illustrative and serves as a case study example). These tank cars can either be transported in one HHFUT (with five locomotives and 100 tank cars) or five HHFTs (consisting of five locomotives, 20 tank cars, and 80 non-hazmat rail cars). The hazmat transportation risks (or release consequences) are interpreted as the expected total casualties caused by a hazmat release per traffic demand (i.e., total risks of all train shipments that are needed to transport 100 tank cars) given train configurations (HHFUT or HHFT), operating speed, traveling distance, and the position of tank cars on HHFTs. In addition to the above conditions, the following assumptions are made:

- In a previous paper (*9*), a sensitivity analysis on train speed was conducted, considering mainline speeds of 25 mph, 40 mph, and 50 mph, which covered the most likely HHFT/HHFUT speeds under 49 CFR 174.310 to 312 regulations. The train speed in yards was set to 15 mph, regardless of changes in mainline speeds. The sensitivity analysis results indicate that total expected casualties increase with mainline operating speed, though changing the speed does not alter the ranking of each scenario. Because the sensitivity analysis was already conducted in the previous paper, the train speed on mainlines in this paper is assumed to be 25 mph (the average derailment speed according to historical derailment data from 1996 to 2018) (*40*). However, as indicated by the sensitivity analysis, using other speeds, such as 40 mph or 50 mph, should not change the relative ranking among different scenarios.
- Locomotives weigh 212.5 tons, and loaded railcars are assumed to be 143 tons (either a tank car or a non-hazmat rail car).
- The gallon capacity of a DOT-117 tank car is assumed to be 30,000 gallons. In this study, the DOT-117 tank car is used as an illustrative example, given that 57% of all rail tank cars transporting DOT Class 3 flammable liquids used the DOT-117 or DOT-117R design (*2*). It is crucial to note that the methodology introduced in this paper is not exclusive to DOT-117 tank cars. The proposed approach can be readily extended to encompass any tank cars capable of transporting DOT Class 3 flammable liquids, with adjustments to the conditional probability of release (CPR) value. It is understood that different Class 3 flammable liquids may be transported primarily in different tank car specifications. In our research, we use a single tank car type (DOT-117) for our risk assessment given the important role DOT-117 tank car specifications play in current and future Class 3 hazmat transportation.
- Tank cars are placed as a block (consecutive and adjacent railcars) in the HHFT.
- The transportation scenario involves a single type of hazardous material per train, thereby excluding consideration of material interactions during a release event.
- Kang et al. (*9*) found that only a very small portion of derailments resulted in more than 20 derailed railcars. Thus, in this paper, we assume the maximum number of railcars derailed is 20 per train derailment.
- There are three classification yards per train shipment over 400 mi for an HHFT, and all are assumed to be flat yards. We do not include hump yards since this paper mainly focuses on the effects of tank car placement strategies. An HHFT is assumed to switch its train consist in the origin (first) and the intermediate (second) classification yards, but not in the destination (third) yard. Thus, there are two yard-switching events per train shipment from the origin to the destination. For each train shipment, an HHFT would depart from the origin yard, arrive at the intermediate yard, depart from the intermediate yard, and then arrive at the destination yard and end its

Table 1. Summary of Case Study Scenarios

Scenario	Train type	Number of trains needed to transport 100 tank cars	Number of terminals or classification yards	Tank car position
1	HHFUT	1	1 origin 1 destination	At 6th to 105th positions in a train
2	HHFT	5	1 origin	At 6th to 25th positions in a train
3			1 intermediate	At 26th to 45th positions in a train
4			1 destination	At 46th to 65th positions in a train
5				At 66th to 85th positions in a train
6				At 86th to 105th positions in a train
7				At positions with the lowest probability of derailing on mainline segments
8				At positions with the highest probability of derailing on mainline segments

Note: HHFUT = high-hazard flammable unit train; HHFT = high-hazard flammable train.

shipment. This process consists of four A/D events. In contrast, an HHFUT only experiences one A/D event when departing from the origin and one A/D event when arriving at the destination (the yard-switching operation in the origin yard to assemble the HHFUT is excluded from the HHFUT risk calculation).

- Tank cars switching in classification yards use the "switch en masse" approach as discussed in Kang et al. (*9*). Generally, the "switch en masse" approach assumes that tank cars are switched in the most complicated environment, where there are non-hazmat rail cars in front of and behind the block of tank cars.
- According to Treichel et al. (*41*), the CPR for a DOT-117 tank car in an FRA-reportable train derailment is 0.043. This value is used in this paper to calculate release probability. The CPR for A/D and yard-switching events is multiplied by a factor of 0.35 to reflect the relatively low operating speed in terminals and yards.
- The derailment rates and parameters used in this paper come from previous work (*9*, *38–40*, *42*, *43*). This paper does not focus on the development of these parameters. Instead, it investigates the impacts of tank car placement and train configuration on transportation risks.
- Kang et al. (*9*) assumed that the released hazmat (DOT Class 3 flammable liquids, specifically) in the spill footprint eventually ignites, which overestimated the total consequences by making the conservative assumption that all flammable hazmat releases lead to fire. In contrast, this paper assumes that once a tank car releases flammable liquids, there is a corresponding probability that this release will result in a fire event depending on different spill sizes. In addition, similar to Kang et al. (*9*), if a hazardous material release occurs following a derailment incident, we assume that the derailment and the release are concurrent events.
- This study only focuses on the consequences of immediate impacts in the event of a derailment.

Eight scenarios were designed to compare strategies using HHFUTs and HHFTs, as well as tank car positions in HHFTs (Table 1). Scenario 1 uses an HHFUT to transport 100 tank cars, while Scenarios 2 to 8 use five HHFTs with different tank car placements. Scenarios 2 to 6 place tank cars at the 6th to 25th, 26th to 45th, 46th to 65th, 66th to 85th, and 86th to 105th positions in a train, respectively. We also construct two extreme cases in which the tank cars are placed at consecutive positions with the lowest probability of derailing on mainline track segments (Scenario 7) and the highest probability of derailing (Scenario 8). The train consists for Scenarios 7 and 8 are determined after obtaining the position-dependent derailment probability. Although Scenarios 2 and 6 have tank cars close to locomotives or at the end of a train, we still include them to demonstrate the risk assessment model and to present how operational practices affect rail hazmat transportation risk. The scenario numbers are tied to various service options to keep track of each scenario throughout this paper (Table 1).

As highlighted above, while the NTSB has provided safety recommendations with regard to the placement of tank cars within trains for crew protection, these guidelines have not yet been formalized into regulations. Consequently, rather than mandating a specific number of buffer cars, our approach involved modeling various placements of the tank car block within HHFTs. For Scenarios 3 to 8, which represent HHFT configurations,

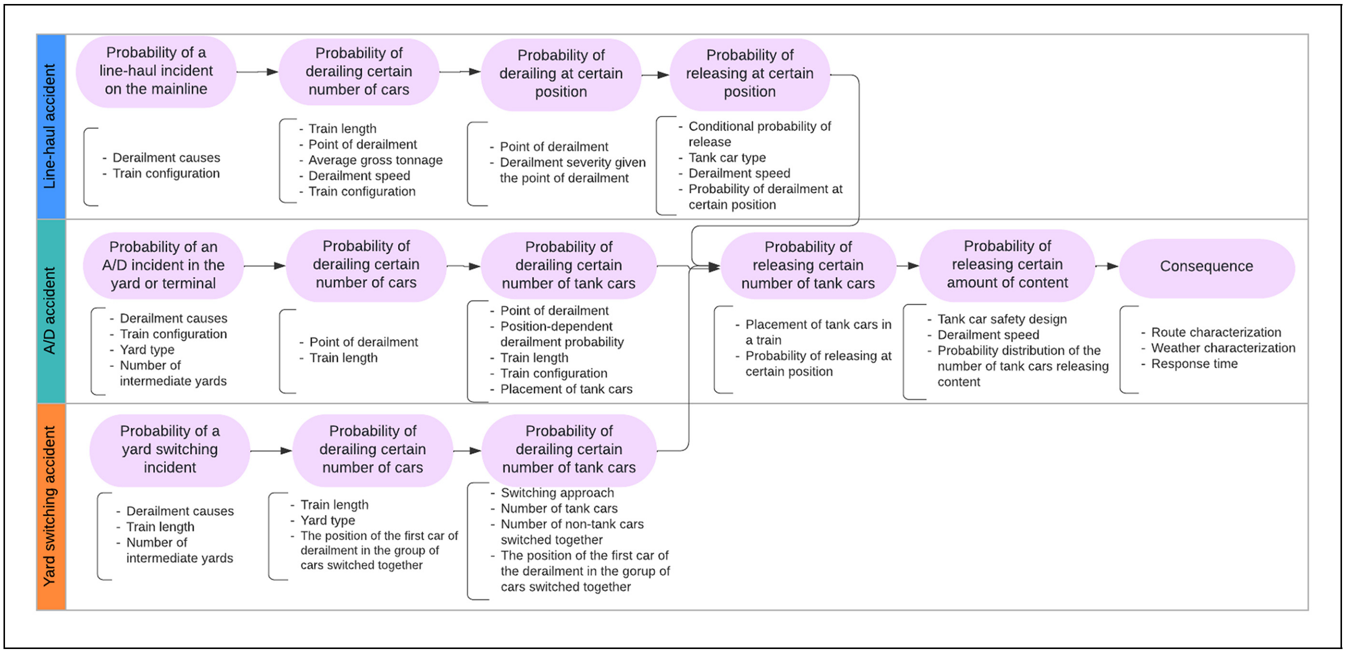

Figure 1. Flow chart of the event chains for different types of accident and the corresponding influencing factors (*9*).
Note: A/D = arrival/departure.

we ensured a minimum of five cars between the locomotives and the tank cars. This design allows us to compare results between HHFUTs and HHFTs under the assumption that the NTSB recommendation is implemented. As for the HHFUT scenario (Scenario 1), based on the sensitivity analysis conducted in a previous study (*43*), adding one buffer car between the locomotives and the tank cars would have very limited (negligible) effects on the final risk consequences. Therefore, we have opted to exclude the inclusion of a single buffer car in Scenario 1, which serves as a control for comparing HHFTs and HHFUTs, with a total of 100 tank cars to be transported, five locomotives, and a total train length of 105.

Methodology

The calculation of hazmat release risk in this paper follows the event-chain-based methodology proposed by Kang et al. (*9*) while improving it by introducing the percentage of release events where a fire event was involved. Given the train configuration, the number of classification yards, train length, route length, average gross tonnage of the train, operation speed, the number of tank cars, their positions, and functions characterizing the amount released, and affected populations, the methodology described in Figure 1 estimates the total expected casualties (as risks) associated with transporting a certain amount of hazmat.

Since the event-chain-based hazmat risk calculation methodology consists of multiple developments of probabilistic models, this paper refers to Kang et al. (*9*) for detailed information about individual component model derivation. The consequence model from Kang et al. (*9*) proposed a hypothetical consequence model based on three representative real-world locations with varying population densities and release sizes. It evaluates the effects of uncontrolled fire spread. When calculating the expected consequences given the probability distribution of the amount released, Kang et al. (*9*) assumed that a train release incident would always result in a fire. This paper replaces this assumption by exploring the percentage of tank cars exposed to fire in release events. Tank car damage and release information from the Tank Car Accident Database (TCAD) is used for this assessment (*41*). All studied release events are categorized into three groups based on the amount of lading loss: small spill releases (0–30,000 gallons); medium spill releases (30,000–90,000 gallons); and large spill releases (more than 90,000 gallons). These three categories correspond to the release incidents that spill all lading from one-, three-, and five-tank cars (note that each DOT-117 tank car in this study has an assumed capacity of 30,000 gallons). Figure 2 shows the number of casualties caused by hazmat release from one-, three-, and five-tank cars using the consequence model presented in Kang et al. (*9*). We consider the maximum amount released to be 150,000 gallons because practical hazmat release events rarely release more than 150,000 gallons of a chemical. In addition, we use consequence models based on crude oil spills and do not distinguish between different

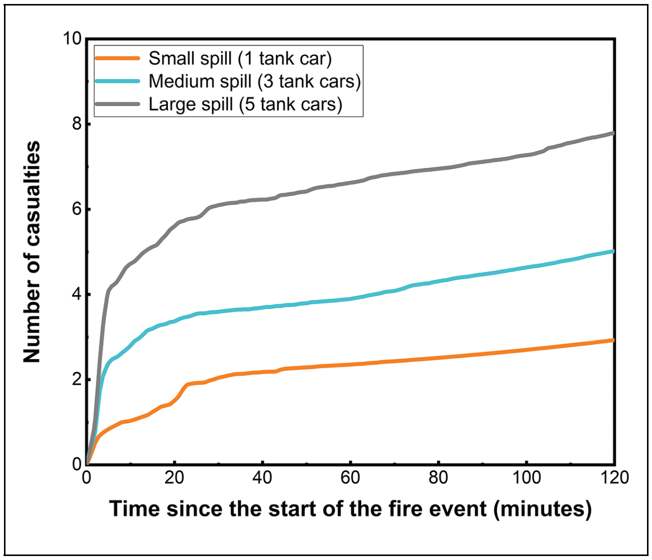

Figure 2. Casualties from fire spread analyses (*9*).

Table 2. Estimated Percentage of Release Events where a Fire was Involved

Category	Amount released (gallons)	Percentage of release incidents where a fire was involved (%)
Small spill	0–30,000	1.5
Medium spill	30,000–90,000	10
Large spill	More than 90,000	25

packing groups (*9*). It is also assumed that the expected number of casualties is not affected by the type of Class 3 chemicals, given the same quantity of release. This assumption stems from the constraints of the referenced fire hazmat release consequence model presented in Kang et al. (*9*). Details on key assumptions of the consequence modeling are provided in the Research Limitations section.

Table 2 shows the percentage (or probability) of releases from each release size category involved in fire events derived from the empirical tank car release data (*41*). These percentages indicate that lower-severity releases tend to have a lower probability of fire involvement than higher-severity releases, which is consistent with practical expectations. Note that the percentages shown reflect overall spill scenarios and do not account for chemical properties and tank car features because of the limitations in size and resolution of the empirical hazmat tank car release data.

The expected total casualties t min after the release incident are calculated by the sum of the expected casualties from a possible small, medium, or large spill:

$$TC(t) = \sum_{0<x\leq 150,000} P_{\text{re}}(x) \times P_{\text{fire}}(x) \times C(x,t) \quad (1)$$

where

$TC(t)$ is the expected total casualties after t min caused by a release incident,

$P_{\text{re}}(x)$ is the probability of releasing x gallons of contents in total from all releasing tank cars, (this term can be obtained following the event chain in Kang et al. [*9*] [Figure 1]),

$P_{\text{fire}}(x)$ is the percentage of releases involving fire when the train releases x gallons in total (Table 2),

$C(x,t)$ is the expected total casualties caused by releasing x gallons of content t min after the event start, and

$t \in [0, 120]$ in min.

In Equation 1, the value of $C(x,t)$ can be obtained from Kang et al. (*9*) after 120 min of a train incident:

$$C(x,120) = \begin{cases} 0 \text{ if } x = 0 \\ 2.928 \text{ if } 0 < x \leq 30,000 \\ 5.018 \text{ if } 30,000 < x \leq 90,000 \\ 7.791 \text{ if } 90,000 < x \leq 150,000 \end{cases} \quad (2)$$

Let the operator $\lceil x \rceil$ be the smallest integer greater than or equal to x. The total expected consequences (quantified as the expected casualties in Kang et al. [*9*]) per traffic demand (defined as the total shipments needed to transport δ tank cars) can be calculated by:

$$TC_{\text{Final}}(t) = \left(\sum_{\forall i} (TC_{\text{mainline}}(\text{t}) \times L_i) + TC_{\text{Yard/Terminal}}(t) \right) \times \left\lceil \frac{\delta}{\text{c}} \right\rceil \quad (3)$$

where

$TC_{\text{Final}}(t)$ is the total consequences per traffic demand t min after the start of the fire event,

$TC_{\text{mainline}}(t)$ is the total casualties per train shipment on the mainline segment i using an HHFUT,

$TC_{\text{Yard/Terminal}}(t)$ is the total casualties per train shipment during A/D and yard-switching events (if applicable),

L_i is the length (in miles) of track segment i,

δ is the number of tank cars that need to be transported, and

c is the capacity of the train, that is, the number of tank cars a train can transport.

Note that $TC_{\text{mainline}}(t)$ and $TC_{\text{Yard/Terminal}}(t)$ can be obtained from Equation 1 by applying the corresponding parameters distinguishing between HHFUTs and HHFTs on mainlines or in yards and terminals. For HHFUTs, $TC_{\text{Yard/Terminal}}(t)$ only contains the total expected casualties from A/D risks, while for HHFTs, it consists of A/D risks and yard-switching risks.

Table 3. A/D Derailment Rate for HHFUTs and HHFTs

Metric unit	Metric unit proportion (9)	The number of A/D events involved per train shipment	The number of A/D train derailments per million train A/D events (9)	The A/D derailment probability per train shipment (following the methodology in Kang et al. [9])
HHFUT				
Train-mile cause	62.8%	2 (leaving the origin terminal and arriving at the destination terminal)	126.31	2.53E-04
Car-mile cause	37.2%	2 (leaving the origin terminal and arriving at the destination terminal)	1.22	2.44E-04
HHFUT total	62.8% x 2.53E-04+37.2%x2.44E-04=			2.49E-04
HHFT				
Train-mile cause	78.1%	1 (at origin yard) + 2 (at intermediate yards) + 1 (at destination yard)	126.31	4.76E-04
Car-mile cause	21.9%	1 (at origin yard) + 2 (at intermediate yards) + 1 (at destination yard)	1.22	8.08E-04
HHFT total	78.1%x4.76E-04+21.90%x8.08E-04=			5.48E-04

Note: A/D = arrival/departure; HHFUT = high-hazard flammable unit train; HHFT = high-hazard flammable train.

The relationships between the number of casualties and time, based on small, medium, and large spills, were calculated in Kang et al. (*9*). These casualty assessments were derived from a series of fire spread analyses conducted at rural, suburban, and urban sites along a rail shipping route. Smoke inhalation injuries constitute the majority of casualties. The fire spread analyses considered different size crude oil spills as the initiating event and different wind characteristics that influenced the fire spread behavior. Simple corrections were applied to the analyses to account for evacuations of people from the fire zone and seasonal variation in the potential for fire spread. Estimates were applied for the relative weights on the distribution of rural/urban areas along the route and the distribution of wind speeds. The fire spread analyses, however, did not consider packing group and operational considerations such as speed restrictions in urban areas. Given the limited nature of the consequence analysis performed, it is best suited to evaluating the relative risk for different operating conditions (e.g., HHFUTs versus HHFTs or position of hazmat with the train) rather than evaluating the absolute consequence values for shipping flammable liquids on the freight rail network.

Risk Calculation

Derailment Likelihood

According to the methodology described in Kang et al. (*9*), the line-haul train derailment rates on a 1-mi mainline segment per train shipment are 8.53E-07 and 9.54E-07 for HHFUTs and HHFTs, respectively. This indicates that traversing the same distance, the risk of a train derailment for the HHFUT is slightly smaller than for the HHFT. Following the paper by Kang et al. (*9*), the A/D derailment rates for each train are calculated separately for the HHFUT in terminals and the HHFT in yards (Table 3). Table 3 indicates that during an A/D event, an HHFT's derailment rate is twice that of an HHFUT. The train derailment rates during the yard-switching events per train shipment (only for HHFTs) are calculated and shown in Table 4. Since these derailment rates are very low, they are estimated as derailment probabilities. During yard-switching events, the train consists of 19 non-hazmat rail cars, followed by 20 hazmat tank cars. The reason for considering 19 non-hazmat rail cars in front of 20 hazmat tank cars is that 19 is the largest number of non-hazmat rail cars that may affect the derailment of tank cars (as we have assumed that the maximum number of railcars derailed is 20). More details are discussed in Kang et al. (*9*). The train consist during yard-switching events does not include locomotives since a switch engine hauls the train. Comparing Tables 3 and 4, we found that an HHFT encounters more significant risks when arriving at or departing from yards than when tank cars are switched and sorted in classification yards.

Position-Dependent Derailment Probability

According to Kang et al. (*9*), the position-dependent derailment probability at each train position is calculated for line-haul events on mainline segments and A/D events in yards and terminals (Figure 3). The train consist for Scenario 7 (tank cars at consecutive positions with the lowest probability of derailing) can then be

Table 4. The Yard-Switching Derailment Rate for the HHFT Per Train Shipment

Yard-switching approach	Number of cars involved per yard-switching event	Number of yard-switching events per train shipment	The number of yard-switching derailments per million cars processed in yards (9)	The probability of the yard-switching derailment per train shipment
Switched in masse	19 non-hazmat rail cars and 20 tank cars	1 (at origin) and 1 (at the intermediate yard)	6.38	4.98E-04

Note: HHFT = high-hazard flammable train.

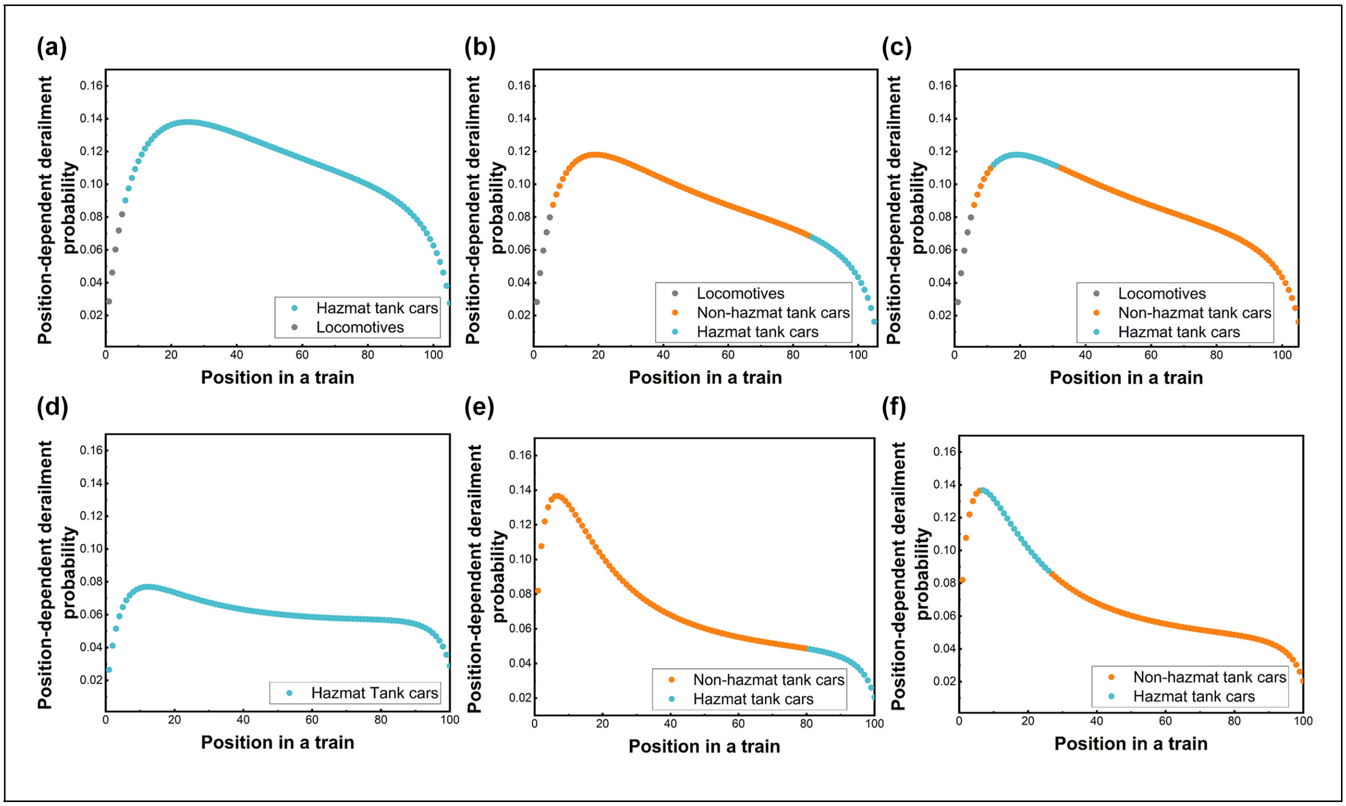

Figure 3. Position-dependent derailment probability during line-haul events and A/D events: (*a*) unit train, incidents on mainlines, Scenario 1; (*b*) manifest train, incidents on mainlines, Scenario 7 (or Scenario 6); (c) manifest train, incidents on mainlines, Scenario 8; (*d*) unit train, A/D incidents in terminals, Scenario 1; (e) manifest train, A/D incidents in yards, Scenario 7 (or Scenario 6); and (*f*) manifest train, A/D incidents in yards, Scenario 8.
Note: A/D = arrival/departure.

determined based on the probability distribution of derailing on mainline segments. Similarly, the train consist for Scenario 8 on mainlines can also be determined. Coincidentally, Scenarios 6 and 7 have the same train consist. Thus, these two scenarios are combined and represented by Scenario 6. The train consists for each scenario during various events are drawn in Figure 4. Note that the train consist considered in the line-haul risk calculation includes five locomotives, but A/D and yard-switching events exclude locomotives. This is because A/D and yard-switching events occur at reduced speed and thus we exclude locomotives in the risk assessment. Figure 3, *c* and *f*, reveal that the top 20 positions with the highest probability of derailing in HHFTs are not the same during line-haul events and A/D events. For line-haul events, they are the 12th to 31st positions (counting locomotives). In contrast, for A/D events, they are the 2nd to 21st positions (not counting locomotives).

Number of Tank Cars Releasing Contents Per Derailment

Once a train derailment occurs, the HHFUT has a greater probability of at least two tank cars releasing

During line-haul and A/D events	Scenario 1	
	Scenario 2	
	Scenario 3	
	Scenario 4	
	Scenario 5	
	Scenario 6 (7)	
	Scenario 8	
During yard-switching events	Scenarios 2, 3, 4, 5, 6, 7, 8	

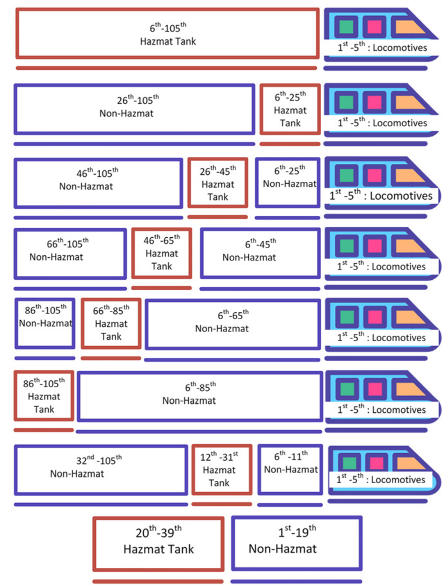

Figure 4. Train consists for each scenario during line-haul events, A/D events, and yard-switching events.
Note: A/D = arrival/departure.

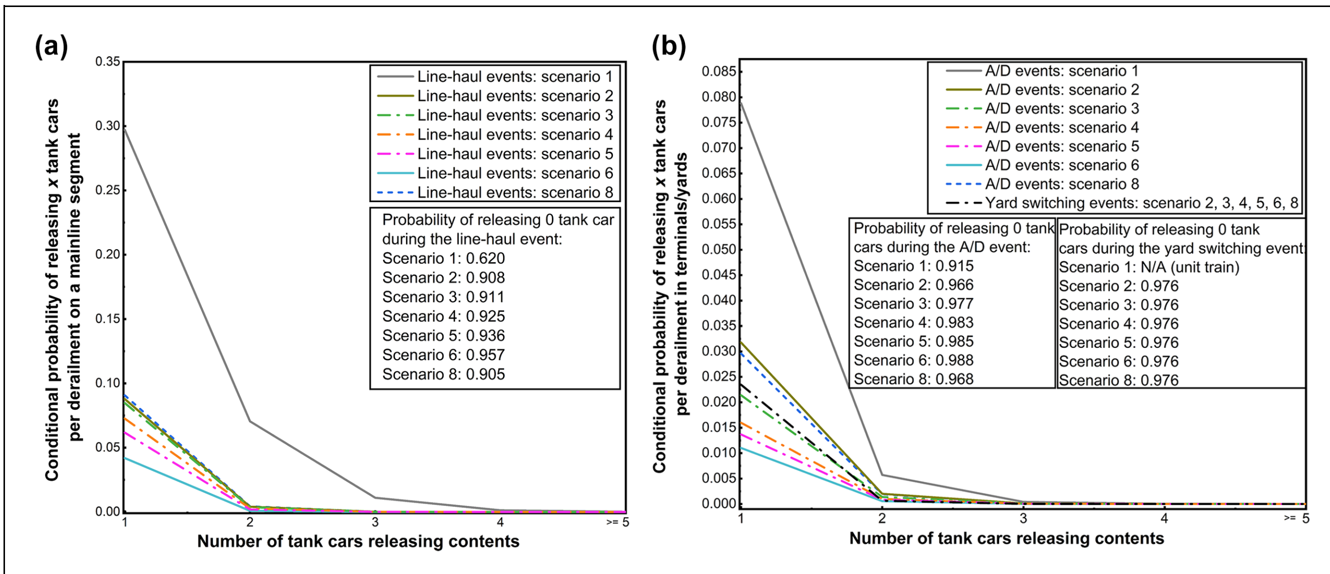

Figure 5. Conditional probability distribution of the number of tank cars released given a train derailment on mainline or in yards and terminals: (*a*) during line-haul events on mainline segments; and (*b*) during A/D events for HHFUTs, during A/D events or yard-switching events for HHFTs.
Note: A/D = arrival/departure; HHFUT = high-hazard flammable unit train; HHFT = high-hazard flammable train.

than the HHFT for both line-haul and A/D events (Figure 5). For HHFTs, the service option that puts all tank cars at the positions with the highest probability of derailing (Scenario 8) has the greatest probability of release. However, there is only a slight difference between Scenarios 2 (tank cars are placed at the front of the train) and 8 (Figure 5). This indicates that placing tank cars at the front of the train has a relatively higher release probability than Scenarios 3 to 7. This service option also puts the train crew at risk of hazmat exposure, which

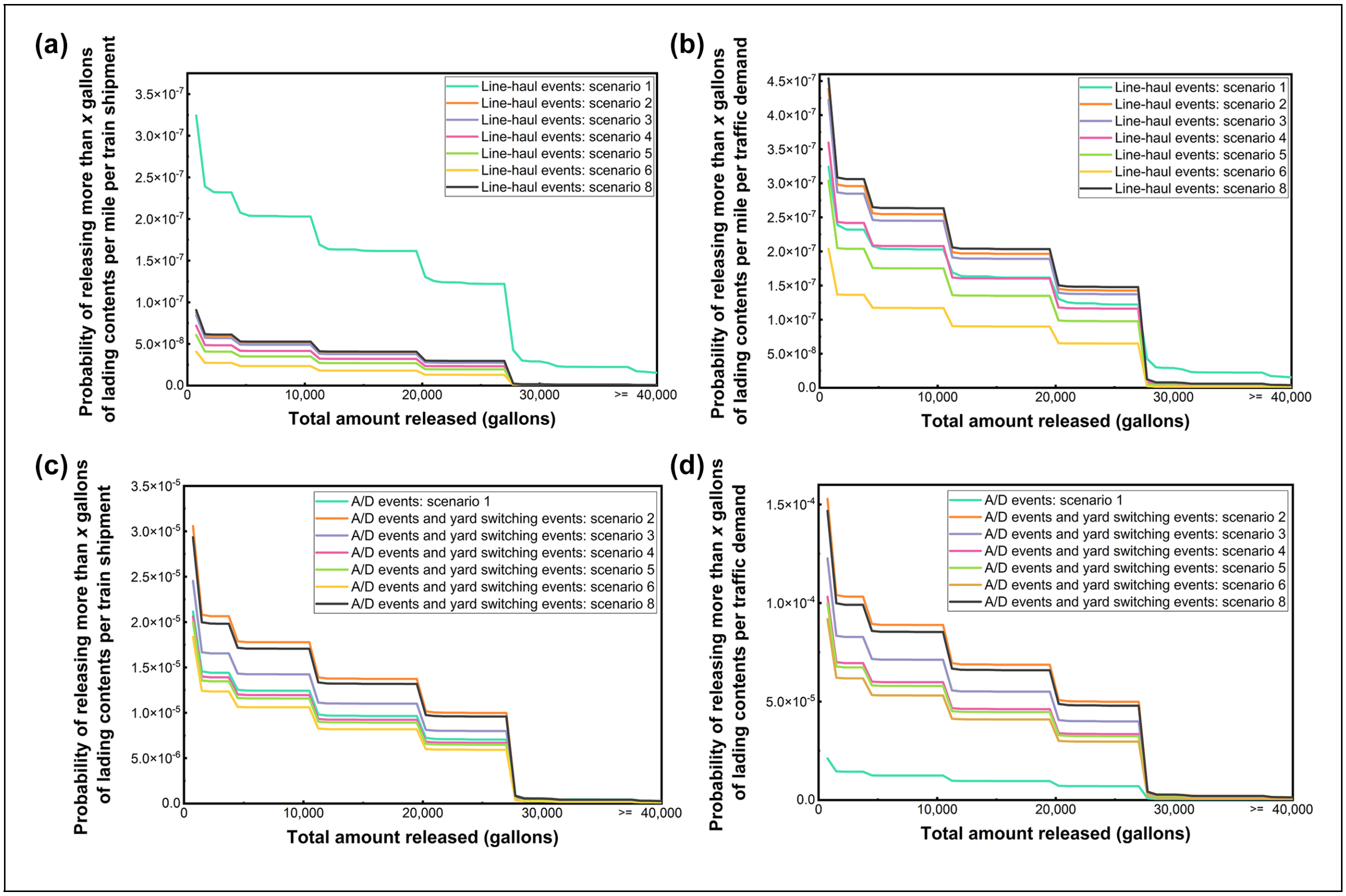

Figure 6. Reverse cumulative distribution of the amount released: (*a*) during line-haul events on mainline segments (per mile per train shipment); (*b*) during line-haul events on mainline segments (per mile per traffic demand); (*c*) during A/D events for HHFUTs, during A/D events and yard-switching events for HHFTs (per mile per train shipment); and (*d*) during A/D events for HHFUTs, during A/D events and yard-switching events for HHFTs (per traffic demand).
Note: A/D = arrival/departure; HHFUT = high-hazard flammable unit train; HHFT = high-hazard flammable train.

makes it even riskier. For line-haul and A/D events, moving tank cars from the front or middle (Scenarios 2, 3, and 8) to the end of the train (Scenarios 4, 5, and 6) could reduce the probability of a significant release incident. Different HHFT scenarios seem to result in similar numbers of tank cars releasing in yard-switching accidents as compared with the A/D events, given a train derailment incident occurs. In Figure 5*b*, Scenarios 2 to 8 have the same probability of a certain number of tank cars releasing during yard-switching events because the train consists during yard-switching events are the same for all service options with HHFTs (Figure 4).

Quantity of Release Per Train Shipment

Figure 6*a* reveals that given a line-haul train derailment, the HHFUT experiences a higher probability of releasing a significant amount of content than HHFTs since each HHFUT carries 100 tank cars. In comparison, an HHFT only carries 20 tank cars. However, this is different from the total amount released when transporting all 100 tank cars using HHFTs: service options using HHFTs require five train shipments in total. As expected, among all service options or scenarios with HHFTs, if we only consider one train shipment, Scenario 8 (placing all tank cars at positions with the highest probability of derailing on mainline segments) generates the most significant likelihood of releasing a greater amount of content. All subfigures in Figure 6 show that the likelihood of releasing a certain amount of content for Scenario 8 is almost twice as large as Scenario 6 (placing all tank cars at positions with the lowest probability of derailing on mainline segments). Note that an HHFUT only experiences A/D risks in terminals, while an HHFT faces both A/D and switching risks in yards. This explains why, in Figure 6*c*, while an HHFUT carries many more tank cars than an HHFT, the amount released by an HHFUT in terminals per train shipment (Scenario 1) is similar in size to service options with HHFTs in yards per train shipment (Scenarios 2 to 8).

Table 5. Ranking of the Scenarios by Total Transportation Risk Per Traffic Demand for Transporting 100 Tank Cars

Scenarios	Casualties			Ranking (ascending, lower risk to higher risk)
	On mainlines (per traffic demand)	In terminal and yard (per traffic demand)	Total	
1 (HHFUT)	4.092E-06	4.778E-07	4.57E-06	3
2 (HHFT)	3.685E-06	3.247E-06	6.93E-06	6
3 (HHFT)	3.534E-06	2.587E-06	6.12E-06	5
4 (HHFT)	2.961E-06	2.155E-06	5.12E-06	4
5 (HHFT)	2.466E-06	2.083E-06	4.55E-06	2 (second lowest risk which is more practical)
6/7 (HHFT)	1.614E-06	1.887E-06	3.50E-06	1 (lowest risk, which is not practical)
8 (HHFT)	3.826E-06	3.799E-06	7.63E-06	7 (highest risk)

Note: HHFUT = high-hazard flammable unit train; HHFT = high-hazard flammable train.

In comparison, Figure 6, *b* and *d*, show the total amount released when transporting 100 tank cars on mainlines and in terminals and yards, respectively. Again, Scenario 1 requires one HHFUT to transport 100 tank cars, while Scenarios 2 to 8 require five HHFTs. Figure 6*b* shows that Scenarios 6, 5, and 1 are the three service options with the lowest total amount released, with Scenarios 6 and 5 using five HHFTs and Scenario 1 using one HHFUT. However, Figure 6*d* reveals that although Scenarios 6 and 5 (with five HHFTs) have relatively less amount released on mainlines per mile per traffic demand, Scenario 1 (with one HHFUT) has the lowest amount released in terminals and yards since HHFUTs only experience A/D risks in terminals. In contrast, HHFTs encounter additional yard-switching risks.

Total Consequences and Comparison Among Scenarios

Table 5 shows the risk calculation of a train incident when transporting 100 tank cars over 400 mi by rail using either one HHFUT or five HHFTs. The service option of running five HHFTs and placing tank cars at positions with the lowest probability of derailing (Scenario 6/7) has the lowest risk. Considering the risk of derailment resulting from "tail-end heavy" conditions and crew safety concerns in any rear-end caboose (if present), placing tank cars at the 66th–85th positions of the HHFT (Scenario 5) is also preferable compared with the HHFUT service option. Service options that place tank cars at the head end or middle of a train (Scenarios 2 to 4 and 8) have greater transportation risks. The case study shows that the risk of Scenario 8 (placing tank cars at positions with the highest probability of derailing) is twice that of Scenario 6 (the scenario with the lowest risk).

While placing tank cars at the end of an HHFT (Scenario 6) is not preferable because of safety concerns around crew members and tail-end derailment, constructing a train consist that satisfies the practical guidance (for example, Scenario 5 which places 20 tank cars at the 66th to 85th positions in each HHFT) can reduce the total expected casualties by 40.34% compared with the worst-case HHFT service option (Scenario 8). These results showcase how the enhanced comprehensive rail hazmat transportation risk assessment model can assist in decision making on hazmat train make-up and switching planning.

The Impact of Train Length

In accordance with previous research (*42*), the pursuit of economies of scale has encouraged railroad companies to operate freight trains with increased length and weight. Advancements in coupler technology, locomotives, and train braking capabilities have also facilitated this trend. In 1990, trains were capable of transporting more than 120 railcars, and today, technological enhancements enable trains to operate with a capacity exceeding 140 railcars.

In the preceding section, the case study primarily centered on trains comprised of 100 railcars. Within that context, the previous section explored and compared the risks associated with transporting flammable liquids by either a single HHFUT or distributing the tank cars across five HHFTs, each consisting of 20 hazmat tank cars and 80 non-hazmat rail cars.

This section extends the transportation scenario to assess whether train length influences the conclusions drawn in the previous section. Maintaining all other contextual factors consistent with the case study discussed earlier, this section introduces a variation by considering the transportation of a total of 140 tank cars over a distance of 400 mi. These tank cars can be transported either by an HHFUT featuring five locomotives at the head end, followed by 140 tank cars, or by seven HHFTs. Each HHFT is equipped with five locomotives, 120 non-hazmat rail cars, and 20 tank cars. Notably, the positions of the tank cars within the HHFTs can vary significantly. Table 6 shows detailed scenario information for

Table 6. Train Configurations and Train Consists for Transporting 140 Tank Cars

Scenario	Train type	Number of trains needed to transport 140 tank cars	Tank car position
1'	HHFUT	1	At 6th to 145th positions in a train
2'			At 6th to 25th positions in a train
3'			At 26th to 45th positions in a train
4'			At 46th to 65th positions in a train
5'	HHFT	7	At 66th to 85th positions in a train
6'			At 86th to 105th positions in a train
7'			At 106th to 125th positions in a train
8'			At 126th to 145th positions in a train

Note: HHFUT = high-hazard flammable unit train; HHFT = high-hazard flammable train.

Table 7. Ranking of the Scenarios by Total Transportation Risk Per Traffic Demand for Transporting 140 Tank Cars

Scenarios	On mainlines (per traffic demand)	In terminal and yard (per traffic demand)	Total	Ranking (ascending, lower risk to higher risk)
1'	5.727E-06	5.96E-07	6.32E-06	4
2'	5.356E-06	4.58E-06	9.94E-06	8
3'	5.151E-06	3.85E-06	9.00E-06	7
4'	4.410E-06	3.20E-06	7.61E-06	6
5'	3.823E-06	2.95E-06	6.78E-06	5
6'	3.354E-06	2.82E-06	6.18E-06	3
7'	2.897E-06	2.74E-06	5.64E-06	2
8'	1.946E-06	2.52E-06	4.47E-06	1

transporting these 140 tank cars. As the methodology remains consistent, to prevent redundancy, we only present the final results for Scenarios 1' to 8' in Table 7.

As shown in Table 7, Scenario 8', involving the placement of 20 tank cars at the end of HHFTs to transport a total of 140 tank cars in seven HHFTs, continues to exhibit the least potential casualty risks. Following closely are Scenarios 7' and 6', where 20 tank cars are placed between the 106th to 125th and 86th to 105th positions, respectively, in seven HHFTs, each carrying 140 rail cars. Subsequently, Scenario 1' ranks as the fourth lowest risk option, involving the use of an HHFUT to transport all 140 tank cars. On comparing the results presented in Tables 5 and 7, a consistent conclusion emerges across both sets of scenarios (1 to 8 and 1' to 8'): the service option of using a single HHFUT occupies a mid-level position when contrasted with service options involving multiple HHFTs with tank cars positioned in different blocks, all intended for the transportation of a fixed number of tank cars.

More specifically, the results in Tables 5 and 7 provide insights into the impact of increasing train lengths on the overall casualty risk of transporting a fixed amount of hazmat (Class 3 flammable liquids, in this case). For the HHFUT Scenarios 1 and 1', increasing the train length from 100 to 140 hazmat railcars (a factor of 1.4) corresponds to an increase in the total transportation risk from 4.57×10^{-6} to 6.32×10^{-06} (a factor of 1.38). This result represents a proportionate increase in risk relative to the increase in train length. This also indicates that transporting 700 tank cars in five HHFUTs of 140 railcars presents a similar, even slightly smaller, total transportation risk compared with transporting 700 tank cars in seven HHFUTs each comprised of 100 railcars. The longer HHFUTs exhibit a slight economy in that fewer train-miles are required per hazmat railcar shipped, and therefore there is a lower per-hazmat-railcar likelihood of derailments linked to causes varying with train-miles. At the same time, one car-mile is still required per hazmat railcar shipped in the longer HHFUTs, and therefore the per-hazmat-railcar likelihood of derailments linked to causes varying with car-miles remains constant. These two effects combine to produce an increase in total risk (38%) that is slightly less than the proportional increase in HHFUT length (40%) for the conditions explored in this case study.

Similar total estimated risks are observed for the best and most practical HHFT scenarios, 5 and 7', where a 40% increase in train length (and total hazmat transported) only increases total transportation risk by 24%. Since the longer HHFTs each contain proportionately fewer tank cars, the tank cars can be located even further away from the positions near the front of the train with the highest derailment risk. Thus, while the number of car-miles and train-miles (and associated likelihood of a derailment) both increase proportionately with increases in HHFT length and the number of HHFTs required, it is even less likely that, given a derailment occurs, the derailment involves the 20 tank cars when the HHFT is longer. The result is that the increase in total risk (24%) is disproportionately less than the increase in HHFT length (40%) for the conditions considered in this case study.

Research Limitations

While this research offers a comprehensive quantitative assessment of the risks associated with transporting Class 3 flammable liquids, incorporating various railroad operational characteristics, it has several limitations. These arise from the inherent complexity of transporting flammable liquids and variations in railroad tank car features. Below, we outline these limitations and the assumptions made to address them. Furthermore, some of these limitations present opportunities for future research, which are also discussed.

Given this paper's specific focus on Class 3 flammable liquids as hazmat, it applies the definition of unit trains and manifest trains to HHFUTs and HHFTs. HHFTs and HHFUTs operate under distinct conditions, with unique equipment requirements, and on different routes compared with other hazmat unit or manifest trains transporting different commodities or mixtures thereof. According to 49 CFR § 172.820, a rail carrier must conduct an annual route analysis to assess safety and security risks along transportation routes. This paper uses a route analysis within a consequence model, building on prior research (*9*). It uses established toolsets developed for evaluating consequences of military or terrorist attacks (such as detonations) and industrial accidents (e.g., hazmat spills, fires). These toolsets include the Hazard Prediction and Assessment Capability (HPAC) with its associated analysis modules and the Nuclear Capabilities Services (NuCS) framework.

This paper uses the HPAC and NuCS toolsets to analyze derailment events involving flammable liquid releases at hypothetical locations with different population densities and release sizes. Derailment sites are selected along a single rail line within a region that includes at least 25 metropolitan areas from the NuCS database, which fully characterizes ground geometry, buildings, and vegetation density. Three representative locations are chosen based on urban (1%), suburban (4%), and rural (95%) track percentages, and the database provides the necessary input data for these sites. This method simplifies the inclusion of all safety and security factors from the annual route analysis, acknowledging that the case study is a simplified model compared with real-world operations. Future studies should consider a more sophisticated route analysis for more accurate comparisons.

In this paper, casualty estimates were derived from a narrowly focused assessment primarily evaluating fire spread risks. Given its limited scope, this assessment is better suited for assessing relative risks across different operating conditions (e.g., HHFUTs versus HHFT or hazmat position within the train) rather than providing absolute consequence values for the transportation of flammable liquids on the freight rail network.

Given that this paper builds on the established model proposed by Kang et al. (*9*), it is limited in scope as it only considers one type of tank car (specifically DOT-117) and one type of hazmat. Future studies could address this limitation by incorporating a broader range of scenarios. For instance, many HHFUTs primarily consist of ethanol or crude oil shipments. Therefore, future research could design new scenarios that consider a combination of DOT-117 and DOT-111 tank cars in HHFTs transporting different types of hazmat. Additionally, comparing HHFTs with HHFUTs, which mostly consist of DOT-117 tank cars transporting crude oil and ethanol, would provide valuable insights. By recognizing these nuances, future studies could offer a more comprehensive understanding of the hazards associated with hazmat transportation by rail and contribute to the development of targeted safety measures and regulatory frameworks.

It is important to note that this risk assessment analysis is a practical study to compare the expected consequences resulting from changes in derailment severity and the amount of hazmat released when transporting Class 3 flammable liquids in HHFUTs versus HHFTs. The findings outlined in this paper should not be extrapolated to encompass every category of hazmat across all railcar varieties. We would like to emphasize that our paper offers a highly macroscopic perspective. Other researchers can further refine risk analysis by following the event-based methodology we have proposed. However, the proposed framework remains adaptable for assessing best train configurations and positioning strategies tailored to the unique characteristics of different hazardous materials being transported over different shipment distances and involving different numbers of intermediate classification yards.

Another legitimate limitation of this paper is related to data mixing. In this analysis, we used data from all train derailments involving various hazardous materials before the implementation of the Fixing America's Surface Transportation (FAST) Act in 2015 and applied it to a model examining HHFTs and HHFUTs. We chose this approach because limiting the analysis to derailments occurring only after the FAST Act's implementation would have resulted in a sample size too small for meaningful analysis. Additionally, we would not have had the necessary denominator traffic data (i.e., train-miles, car-miles, and ton-miles by HHFT/HHFUT train types) to properly normalize the derailment data and calculate derailment rates. For future studies, researchers could consider using derailment data since 2012, as they reflect current safety standards and operating procedures.

Concluding Remarks

This paper adapts a novel event-chain-based methodology to conduct a practical study that analyzes the risks of transporting DOT Class 3 flammable liquids in HHFUTs versus HHFTs. The DOT-117 tank car is used as an example to perform the case study, but the methodology can be extensively applied to any tank car types that transport DOT Class 3 flammable liquids. Despite variations in puncture resistance and CPR values among different tank cars, the relative risks associated with their positioning is expected to remain consistent. A key reason for this is that, in this paper's methodology, the effects of tank car type are predominantly manifested through CPR values. For example, to examine the expected release risks in the scenario where all tank cars are DOT-111, a practitioner must substitute the DOT-117 CPR value with the one corresponding to the DOT-111. Consequently, we anticipate that the findings and conclusions derived from this study would be applicable to any tank car type tasked with transporting DOT Class 3 flammable liquids.

By quantitatively estimating the total expected consequences following the event chain in Figure 1, this study designs eight scenarios involving different train configurations and tank car placement options. The worst-case and best-case tank car placement options (designed according to position-dependent derailment probability on mainlines) are compared with other random tank car positions for HHFTs. A service option with an HHFUT transporting 100 tank cars in one shipment is also included.

The calculated results for the eight customized scenarios carrying 100 tank cars show that the position of the block of tank cars in an HHFT may significantly affect overall transportation risk. Specifically, an HHFUT could have a higher risk than multiple HHFTs transporting the same amount of hazmat if all tank cars are located at positions with the lowest probability of derailing on HHFTs. However, given the potential derailments caused by excessive weight at the tail-end of the train and crew safety, it is not always practical to place all loaded tank cars at the end of a train (the position with the lowest probability of derailing). If this is the case, the service option with five HHFTs and tank cars placed at the 66^{th} to 85th positions of a train (assuming a train has 100 railcars) could result in lower risk than all other service options. This conclusion (drawn from quantitatively estimating the total expected casualties caused by the derailment and release incident of hazmat trains) is consistent with prior statistical studies (*7*, *36*, *37*) while protecting crews in locomotives and cabooses. In reality, when the train length does not allow for five buffer cars (for example, for HHFUTs), there may be one buffer (non-hazmat) car separating locomotives (crews) and tank cars. The conclusion from this paper still holds since adding one car to a train consisting of 105 cars does not significantly affect the overall total expected casualties (*36*).

The historical data show that a small hazmat spill could have a lower probability of a fire event than a large spill. Our risk methodology considers the distribution of the amount released, the probability of fire events, and the related casualties from the fire. Because an HHFUT carries more tank cars than an HHFT, it could have a larger probability of releasing a significant amount of content during line-haul and A/D events, and a correspondingly greater risk resulting from fire-related casualties.

To assess the impact of train length on our findings, this study conducts a parallel analysis of the shipment of 140 tank cars. The outcomes affirm that the conclusions derived from 100-tank-car scenarios remain consistent in the context of transporting 140 tank cars.

The phase-out of DOT-111 tank cars and the adoption of DOT-117 tank cars represent a pivotal transition in the transportation of hazardous materials by rail. Historically, DOT-111 tank cars have been extensively used for the shipment of various hazardous materials, including Class 3 flammable liquids. However, in view of the safety concerns and regulatory initiatives, particularly in response to high-profile incidents such as the Lac-Mégantic rail disaster in 2013, regulatory bodies have mandated the retirement of DOT-111 tank cars and the implementation of more robust tank car standards. DOT-117 tank cars, designed with enhanced safety features and structural integrity, have emerged as the preferred choice for transporting hazardous materials, offering improved resistance to punctures and thermal protection in the event of an accident. This transition has been phased in gradually, with specific deadlines set for different hazardous material categories. For instance, crude oil shipments transitioned exclusively to DOT-117 tank cars by 2018, followed by ethanol shipments in 2023. By May 1, 2025, all Class 3 Flammable Liquid Packing Group I materials will be exclusively transported in DOT-117 tank cars, with Packing Groups II and III to follow suit by May 1, 2029. Therefore, in crafting the case study scenarios, we opted to spotlight the DOT-117 tank car as an example to underscore its pivotal role in hazmat transportation for the foreseeable future. However, it is worth noting that since this paper focuses on modeling the consequences of hazmat releases by integrating the CPR, adapting the CPR for retrofitted DOT-111 tank cars or, in the future, enhanced DOT-117 tank cars would be a straightforward adjustment that would not alter the underlying framework of the risk model.

According to a recent study (*43*), contemporary trains have grown in length and weight. To capitalize on economies of scale, distributed power (DP) is widely employed. This practice minimizes drawbar forces, enhancing train dynamics and enabling the efficient and safe operation of longer and heavier trains. In this investigation, we exclusively examined scenarios involving the placement of all locomotives at the front end of a train, omitting the consideration of distributed power. However, future research could seamlessly expand and customize this study to explore whether varying the positioning of locomotives, such as placing them in the middle or at the end of the train, significantly influences the derailment rate, distribution of the first derailed vehicle over the length of a train, and the number of railcars derailed given a derailment occurs at a certain position in a train operated with DP.

While this paper provides valuable insights into the transportation of a single type of hazardous material on trains, it acknowledges the limitation of not addressing the complexities of hazmat segregation and the inclusion of buffer cars for trains carrying multiple types of hazardous materials. Future studies could explore these intricate factors to develop advanced models capable of analyzing the transportation of mixed hazmat cargoes. By delving into these complexities, researchers can offer comprehensive insights into optimizing safety measures and risk mitigation strategies for diverse hazmat transportation scenarios.

Another area for potential future research would be an expanded analysis of the consequences of derailment-initiated fires. One difficulty in performing consequence analyses is that often the results are influenced by the most severe events that are extremely rare. One such type of severe consequence that has not been sufficiently evaluated for transporting flammable liquids by rail is the event of an uncontrolled fire spread. Future work could focus on addressing the aforementioned limitations of this paper.

Author Contributions

The authors confirm contribution to the paper as follows: study conception and design: Di Kang, Xiang Liu; data collection: Di Kang, Jiaxi Zhao; analysis and interpretation of results: Di Kang, Jiaxi Zhao, Steven W. Kirkpatrick; draft manuscript preparation: Di Kang, Xiang Liu, Chen-Yu Lin, Zheyong Bian, C. Tyler Dick. All authors reviewed the results and approved the final version of the manuscript.

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