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Probabilistic risk analysis of unit trains versus manifest trains for transporting hazardous materials

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ABSTRACT

When transporting hazardous materials by rail, train types (unit train or manifest train) can influence derailment and release risks in several ways. Unit trains only experience risks on mainlines and when arriving at or departing from terminals, while manifest trains experience additional switching risks in yards. A comprehensive risk assessment methodology is needed to quantitively compare shipments with unit trains and manifest trains, considering both mainline and yard operations. To fulfill this research gap, this paper constructs event chains for line-haul risks, arrival/departure risks, and yard switching risks using various probabilistic models and finally determines expected casualties as the consequences of a potential train derailment and release incident. Five illustrative scenarios are designed to analyze the best and worst cases and compare the transportation risk differences between service options using unit trains and manifest trains. The comparison results indicate that placing all tank cars at the positions with the lowest probability of derailing and switching tank cars alone in classification yards could provide the lowest risk estimate given the same transportation demand.

1. Introduction

The year 2021 has witnessed several train incidents on freight railways involving derailments and leaks of hazardous materials (hazmats): 47 cars of a train carrying combustible fertilizer and asphalt derailed in Sibley, Iowa; 27 cars derailed in Ames, Iowa; and 30 cars derailed in Newberry Township, Pennsylvania. Hazmat release poses a significant threat to surrounding people, property, and the environment. When transporting the same amount of hazmat using the same number of tank cars from the same origin to the same destination, service strategies play an important role in reducing overall transportation risks. One possible strategy uses *unit trains*, usually consisting of 40–120 railcars, carrying the same commodity from the origin *terminal* to the destination terminal. Another possible service strategy uses *manifest trains*, in which railcars from multiple origins and destinations assemble and dissemble between trains at intermediate *classification yards*.

In the context of North American railroads, freight shipments carried by manifest trains require a process of assembling and dissembling, so that railcars bound for the same destination (or intermediate) classification yards are re-sorted into a new train. Railroad classification yards serve as hubs where loaded and empty railcars from various origins are grouped together into blocks of railcars headed for common destinations. These blocks of railcars are then further aggregated to form trains destined for different classification yards on other parts of the network or for local delivery to nearby shippers. The railcar sorting process requires numerous coupling and uncoupling events as groups of railcars are moved between multiple parallel tracks. In the highest-volume classification yards, sorting is accomplished by pushing railcars over small hills, or “humps.” These events typically take place 1) in the main classification yard and its associated tracks used for accumulating railcars into blocks by destination, 2) on the switching lead tracks used to actively sort the railcars and connect the receiving and departure tracks to the classification tracks, or 3) on other ancillary tracks used to process railcars as they pass through the classification yard. The sorting and

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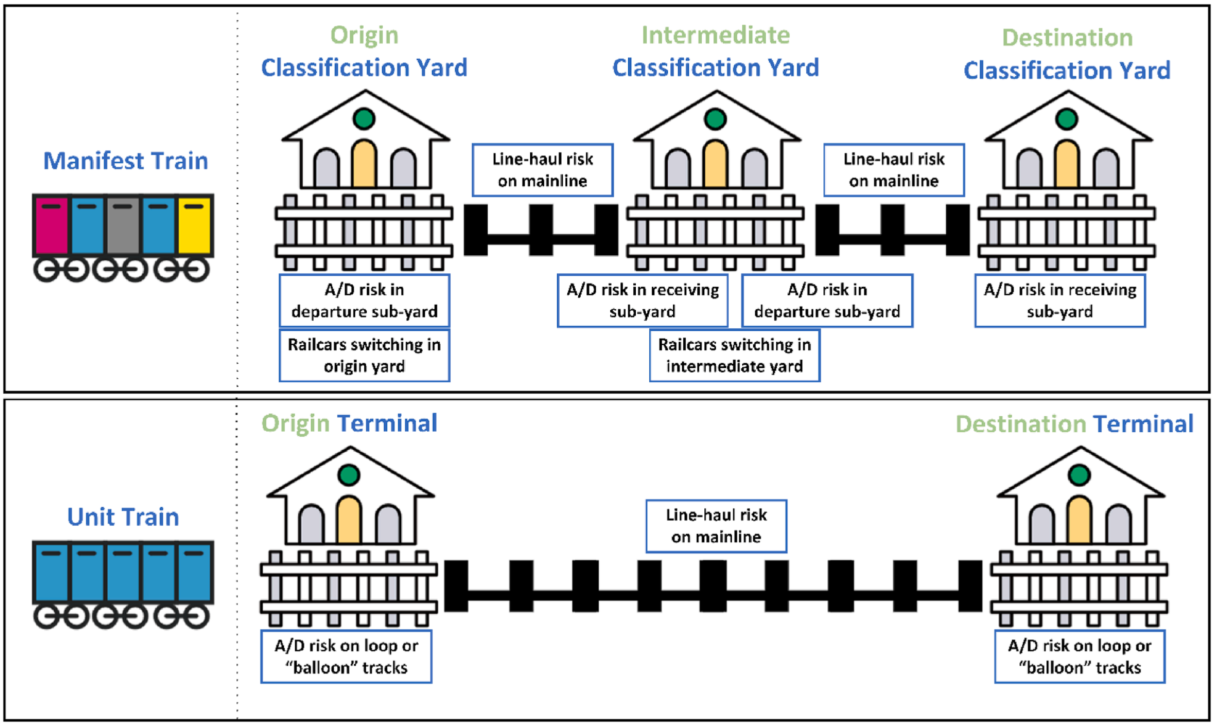

Fig. 1. Types of risks encountered by different train configurations.

switching process by destination in classification yards poses an additional risk of derailment and release. Switching accident severity is generally lesser than a line haul incident due to slower speed and a smaller number of cars being handled.

In addition to the line-haul risk on mainlines, both unit trains and manifest trains encounter derailment and release risks during arrival and departure (A/D) events at loading and unloading terminals and in classification yards. A/D events are operational processes similar to mainline operations but with reduced speed on non-mainline tracks. For unit trains at terminals, A/D events typically occur on loop or "balloon" tracks used to sequentially load or unload each railcar in the unit train as it advances at low speed or on the lead tracks connecting these facilities to the mainline. For manifest trains at classification yards, A/D events typically take place 1) in the receiving sub-yard where manifest trains arrive from the connection to the mainline, 2) in the departure sub-yard where manifest trains depart the classification yard to the mainline, or 3) on the lead and running tracks connecting the receiving and departure sub-yards to the mainline. Fig. 1 depicts all types of risks using either unit trains or manifest trains transporting hazmat.

Only judging based on train characteristics makes it difficult to determine which service option experiences fewer risks than the other. The unit train provides economies of scale and short lead times. It saves time and money by avoiding the complicated assembling and dissembling processes that pose additional risks in intermediate classification yards for manifest trains. However, since unit trains usually have more railcars on one shipment than manifest trains, unit train derailments can result in more cars derailed per accident than manifest trains. Compared to unit train configurations, the placement of hazmat railcars in manifest trains, the switching approach, and the number and type of intermediate classification yards can affect hazmat transportation risks related to derailments and subsequent hazmat release for manifest trains. Previous work has explored transportation risks related to mainlines and yards/terminals separately to some extent (Liu, 2017a; Zhao et al., 2022; Zhao and Dick, 2022), factors that influence mainline and yard risks (Barkan et al., 2003), and accident rates distinguishing between mainlines and yards (Anderson & Barkan, 2004). However, there is no comprehensive methodology that focuses on comparing the transportation risks between unit trains and manifest trains, with consideration of all mainline, yard, and terminal risk components. This highlights the need for further study using more recent data.

The main contribution of this research is: by considering both mainline and yard/terminal operations, this paper builds an event-chain-based probabilistic risk analysis using multiple probabilistic models and the latest derailment rates based on data from 1996 to 2018. Derailment rates and parameters used in various distributions are all estimated based on the Class I railroad annual report financial data, Surface Transportation Board waybill sample data, and mainline and yard/terminal derailments from the FRA Rail Equipment Accident (REA) database. This paper proposes a comprehensive methodology comparing unit trains and manifest trains transporting a given amount of hazmat to answer the following question: given certain combinations of train length, tank car block size, operating speed, tank car placement in manifest trains, yard type, yard switching approach, and tank car design, will one train configuration experience less risk than others? To demonstrate the application of the proposed approach to an actual railway hazmat transportation scenario, this paper also presents a detailed step-by-step case study calculation and comparison using the proposed methodology. Finally, the sensitivity analysis is conducted using various train speeds on mainlines.

The remainder of this paper is organized as follows. Section 2 discusses previous work related to risk analyses of hazardous material trains. Section 3 presents the proposed methodology in detail, considering both mainline and yard components. A case study with five scenarios is conducted using the proposed risk calculation methodology. Section 4 provides detailed calculations of the case study and shows the differences in risk for unit trains and manifest trains. Section 4 also conducts a sensitivity analysis with various operation speeds on mainlines. Section 5 offers the paper's conclusions.

2. Literature review

Existing studies have performed risk analyses of rail transport of hazardous material *on mainlines* based on the event chain (Table 1). They have explored the event chain leading towards the accident, and

Table 1
Summary of findings from previous studies related to risk components on mainlines.

Related events	Author (s)	Data sources	Summary of contributions/limitations
Train accidents	Nayak et al. (1983)	1975–1977, Class 1–6 tracks, U.S.	Found the correlation between FRA track class and train derailment rate.
	FRA (2011)	2000–2011, U.S.	Identified around 389 distinct accident causes.
	Liu et al. (2012)	2001–2010, Class I freight railroads, U.S.	Statistically analyzed derailment data by accident type, track type, and speed.
	Bing et al. (2015)	2004–2008, U.S. railroad network.	Described the event chain leading to hazmat car release; defined, derived, and estimated values for the metrics for risk analysis; concluded that the top three leading accident cause groups were broken rail (14.1 %), track geometry (7.6 %), and wide gauge (5.0 %).
	Liu (2015)	2000–2012, Class I freight railroads, U.S.	Used Poisson distribution to approximately estimate the number of train accidents. The results showed that although broken rails and welds were still the leading derailment cause, they decreased annually.
	Liu (2017b)	2000–2014, freight railroads, U.S.	Developed a log-linear statistical model to estimate the number of train derailments for each cause group considering railroad, season, traffic exposure.
	Zhang et al. (2021)	1996–2018, Mainline freight train derailment data on Class I railroads	Calculated derailment rates of freight unit trains and manifest trains on mainlines.
Derailment severity	Saccomanno and El-Hage (1989), Saccomanno and El-Hage (1991)	1980–1985, Canadian National Railway and Canadian Pacific data	Established position-dependent derailment profiles to determine the probability of derailment for each position and then calculated the derailment severity by train derailment cause.
	Anderson (2005)	1992–2001, Class I and non-Class I railroads, U.S.	Modeled a nonlinear expression to estimate the probability of a freight train derailing at an aggregated level with respect to traffic exposure, train length, and track class.
	Bagheri (2010)	1975–2007, train accident database in U.S.; 1983–2005, train accident database in Canada.	Improved the existing model by considering train configuration.
	Liu et al. (2013)	2001–2010, Class I freight railroad mainlines, U.S.	Built a zero-truncated negative binomial regression model to estimate the conditional mean of the number of cars derailed considering residual train length, derailment speed, and loading factor.
	Liu (2016)	2000–2014, freight railroads, U.S.	Built a statistical model to estimate the number of cars derailed accounting for track class, operational method, annual traffic density level, and year.
	Liu (2017b)	2000–2014, freight railroads, U.S.	Compared the derailment rates and the number of cars derailed by FRA track class, method of operation, and annual traffic density
Number of hazmat cars derailed	Saccomanno and El-Hage (1989), Saccomanno and El-Hage (1991)	1980–1985, Canadian National Railway and Canadian Pacific Railway Data	Adopted a nonlinear regression model to minimize the number of hazmat cars derailed considering different marshaling strategies and corridor conditions.
	Bagheri et al. (2014), Bagheri et al. (2011), Bagheri et al. (2011)	1995–2009, freight railroads, U.S.	Stated that the total number of hazmat cars derailed depends on train length, the number of hazmat cars in a train, and their placement.
	Bagheri et al. (2014), Bagheri et al. (2012)	1992–2006, freight railroads, U.S.	Used a truncated geometric expression to estimate train derailment severity (not position-dependent); investigated the placement of hazmat tank cars in the positions that are less likely to derail;
Probability of Hazmat Car Release	Kawprasert and Barkan (2010)	1992–2001, Class I and non-Class I railroads, U.S.	Estimated the conditional probability of tank car release because of head damage, shell damage, top fitting damage, bottom fitting damage considering train speed.
	Prabhakaran and Booth (2018)	–	Developed a methodology to quantify the performance of reduction in puncture probability considering tank car designs/tank car operating environment.
	Saat and Barkan (2011)	–	Found that more robust tank car designs can reduce tank car release probability.
	Liu et al. (2014)	2002–2011, freight railroads, U.S.	Calculated the probability distribution of the number of cars derailed and the number of tank cars releasing contents based on simplistic assumptions of random placement of hazmat cars and did not account for derailment probability difference by train positions.
	Liu (2017a), Liu et al., (2018)	2002–2011, freight railroads, U.S.	Estimate the probability of a release incident, regardless of the number or quantity of hazmat cars releasing.

risks have been quantified or modeled using different methodologies and historical datasets. However, a comprehensive risk analysis, which would consider all possible risks that a hazmat shipment might experience on both mainlines and in yards/terminals, is still lacking.

Although focus has mostly been given to modeling mainline risks in previous research, there have also been a few studies focusing on yard/terminal risk assessments. Despite the amount of time spent in classification yards, these facilities tend to be deemphasized or excluded in railway hazardous materials transportation risk assessments (Center for Chemical Process, 1995). Of the three aspects of the rail transportation process, the risk of the line-haul movement along mainline routes, intermediate yards, and loading/unloading captures the majority of attention when evaluating risk (Purdy et al., 1988). Glickman & Erkut (2007) argued that while the risk of movement through rail yards cannot be ignored, yard risk receives little attention due to a lack of data to support analysis and the perception of it being a minor risk compared to the mainline. Barkan et al. (2003) calculated railcar derailment rates for both mainlines and yards but concentrated on mainline accidents for subsequent research. Yard accidents were deemphasized since the yard incidents occurred at low speeds and were less likely to lead to hazardous material release (Anderson & Barkan, 2004). In making the decision to focus on mainline train accidents, since the risk of railroad hazardous materials transport is the product of the likelihood of a release event and its consequence (Saat et al., 2014), Barkan et al. (2003) only considered the likelihood half of the risk equation. They did not fully consider the consequence of population exposure, implicitly assuming that it would be identical along mainline routes and surrounding yards and terminals. However, while many mainline route miles are in remote, sparsely populated rural areas, most classification yards are located in urban areas that are moderate to densely populated, increasing human exposure to potential releases (Christou, 1999).

Previous studies of this approach have either ignored the risk in classification yards while focusing on the line-haul route risk or have only acknowledged a potential increase in risk associated with the classification yard train assembly process in a cursory manner as a subject for future research (Bagheri, 2010; Bagheri et al., 2011, 2012; Federal Railroad Administration, 2005). With less focus on railroad yard accident risk, there has been a lack of research analyzing risks throughout shipments, considering both mainline and yard/terminal components. In addition, due to the implementation of unit trains, the derailment severity involves multiple tank cars, which is much more complicated than the hazmat release incident with one tank car. However, because of data limitations, limited prior studies analyze the number of tank cars releasing contents or the total amount released given a train derailment.

To fill this knowledge gap, this paper is the first study to build event chains for line-haul risks, arrival/departure risks, and yard switching risks while considering train configuration. Yard types, train types, yard switching approaches, and a series of probability distributions for each event chain component are discussed in detail when building the probabilistic models. Additionally, the event chain for mainline risk analysis is also extended, modified, and improved. Risks are modeled as the total expected casualties considering route characterization, weather characterization, and evacuation response time. By considering risks on mainlines and yards/terminals for unit trains and manifest trains, this paper provides a solid approach for any train configuration transporting any amount of hazmat on any planned railroad. The proposed methodology can be used as a calculator to guide operational arrangements to reduce the total potential risks encountered.

3. Probabilistic risk analysis methodology

Drawing on previously published work, this paper uses multiple probabilistic models to model the total risk of derailments to push the frontier of rail hazmat research. The probabilistic risk analysis methodology consists of: 1) a derailment-cause-specific model to estimate train-type-specific derailment probability based on U.S. railroad safety data from 1996 to 2018; 2) a truncated geometric statistical model to estimate derailment severity (number of cars derailed); 3) a position-dependent tank car derailment and release probability model based on the point of derailment (i.e., the position of the first vehicle derailed in a train), derailment severity, tank car placement, and tank car safety design; 4) the probability distribution of the total number of tank cars releasing applying a Poisson Binomial distribution model using the above-mentioned position-based tank car release probability; and 5) the estimated amount of hazmat released calculated by the combination of the number of tank cars releasing contents and the amount released per single tank car; 6) expected casualties are finally calculated as a consequence of derailments.

The fundamental operating differences on mainlines and in yards/terminals determine the different components required to model the transportation risks by rail. Fig. 2 shows the event chains for three different types of risks: line-haul risks on mainlines, A/D risks in yards (for manifest trains) or terminals (for unit trains), and yard switching risks (for manifest trains). In this section, three event chains for these three types of risks will be elaborated component-by-component in the following subsections.

3.1. Train derailment probability

A train derailment is an initial event in the chain leading to a final release incident. The probability of a train derailment is approximated by analyzing the historical derailment data from the Class I railroad[1] annual report financial data, Surface Transportation Board (STB) waybill sample data, and yard/terminal derailments from the FRA REA database (Dick et al., 2021). This subsection is divided into two parts presenting train derailment likelihoods on mainlines (Section 3.1.1) and in yards/terminals (Section 3.1.2).

3.1.1. Derailments on mainlines

According to Liu (2015), when traffic exposure is large and the derailment rate (i.e., the number of derailments normalized by the corresponding traffic volume) is relatively low, the probability of train derailment can be numerically approximated by multiplying the derailment rate by the mileage of the train shipment. Thus, the probability of train derailment can be estimated based on the train derailment rate using historical train derailment data and traffic data. The FRA has categorized more than 300 accident causes into five groups based on the circumstances and conditions of accidents (FRA, 2012). The hierarchically organized groups can be classified as track, equipment, human factors, signal, and miscellaneous, with each cause being assigned a unique cause code. In the 1990 s, a study by Arthur D. Little, Inc (ADL) grouped similar FRA accident causes together based on experts' opinions, producing a variation on the FRA subgroups (Arthur D. Little, Inc. (ADL), 1996). Previous studies (Liu, 2015; Liu, 2016; Liu et al., 2012; Schafer & Barkan, 2008) found that the ADL cause groups could be more fine-grained, allowing for greater resolution for certain causes. For example, the FRA combines broken rails, joint bars, and rail anchors in the same subgroup, whereas the ADL grouping distinguishes between broken rail and joint bar defects. Thus, this study uses ADL cause groups to conduct its cause-specific railroad derailment analysis.

The traffic volume data used in this paper is obtained from the Class I railroad annual report financial data and Surface Transportation Board (STB) waybill sample data, which is available for the years 1996 to 2018 at the time of this analysis. STB data did not provide direct identifiers for the train types (e.g., manifest train or unit train). However, we can determine train type by inferring from the information they provided (Dick et al., 2021). We count the number of accidents that occurred by cause category. In total, there were 2,462 unit train derailments and 5,514 manifest train derailments on mainlines over these years. These accidents are classified into 46 cause groups. Table A.1 in Appendix A shows train derailment data from 1996 to 2018 by cause group and train type on Class I mainlines.

This study develops a cause-based train-derailment probability model. First, train derailment causes are classified into three categories: train miles, ton miles, and car miles (railcars only). For example, "broken wheels" could be associated with car miles traveled, and thus the probability of a derailment caused by "broken wheels" should be calculated based on the traffic metric "car miles." In contrast, obstruction-caused accidents may be affected by the number of trains, and thus the probability of a derailment caused by "obstruction" could be calculated based on the traffic metric "train miles."

Let *TRM* denote the set of train-mile-based derailment causes, *TOM* denote the set of ton-mile-based derailment causes, and *CM* denote the set of car-mile-based derailment causes. If a train has L railcars, its gross tonnage is denoted as GW, and it travels on a track segment i with length L_i (in miles). The probability of train derailment due to the c^{th} cause can be calculated by:

[1] As of 2019, the Surface Transportation Board defines a Class I as having operating revenues of or exceeding $505 million annually. (Resource: https://en.wikipedia.org/wiki/Railroad_classes.).

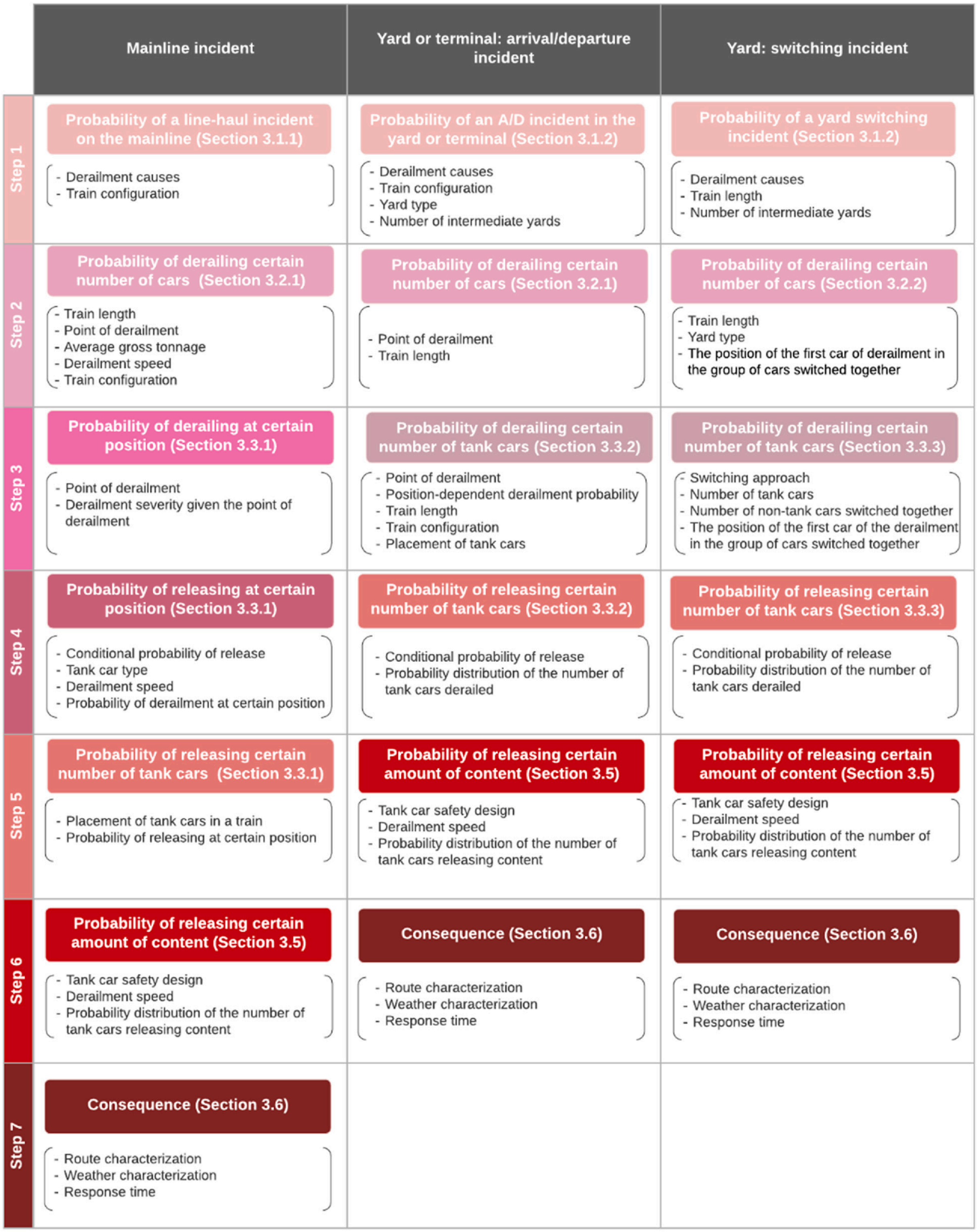

Fig. 2. Flow chart of event-chain-based risk analysis and the related risk components.

Table 2
Derailment rate on mainlines by traffic metric (Zhang et al., 2021).

(a) Unit train	
Metric	Derailments
Derailments per million train-miles	0.85
Derailments per billion gross ton-miles	0.10
Derailments per billion car-miles	8.14
(b) Manifest train	
Metric	Derailments
Derailments per million train-miles	0.67
Derailments per billion gross ton-miles	0.14
Derailments per billion car-miles	11.39

$$P_{i,c|c\in \mathrm{TRM}} \approx d_{\mathrm{TRM}}/1,000,000 \times L_i \times p_c \quad (1)$$

$$P_{i,c|c\in \mathrm{TOM}} \approx d_{\mathrm{TOM}}/1,000,000,000 \times GW \times L_i \times p_c \quad (2)$$

$$P_{i,c|c\in \mathrm{CM}} \approx d_{\mathrm{CM}}/1,000,000,000 \times L \times L_i \times p_c \quad (3)$$

where

$P_{i,c|c\in \mathrm{TRM}}$: the probability that the derailment happens on mainline segment i and is caused by a mainline train-mile-based cause.

$P_{i,c|c\in \mathrm{TOM}}$: the probability that the derailment happens on mainline segment i and is caused by a mainline ton-mile-based cause.

$P_{i,c|c\in \mathrm{CM}}$: the probability that the derailment happens on mainline segment i and is caused by a mainline car-mile-based cause.

d_{TRM}: the number of mainline train derailments per million mainline train-miles (Table 2).

d_{TOM} : the number of mainline train derailments per billion mainline gross ton-miles (Table 2).

d_{CM} : the number of mainline train derailments per billion mainline car-miles (Table 2).

p_c: the fraction of mainline train derailments due to c^{th} cause in the total number of mainline derailments (Table A.1 in Appendix A).

L: train length, i.e., number of railcars in the train.

L_i: the length (in miles) of the track segment i where the train will travel from the origin to the destination.

GW: gross tonnage (in tons) of the train (including lightweight and lading).

The derailment rate by traffic metric data shown in Table 2 is calculated by Zhang et al. (2021) using FRA-reportable Class I mainline train derailment data for the years 1996–2018. Since the train derailment probability per train shipment is very minimal, the probability of a train derailment on mainline segment i (denoted as $PTD_{i,\mathrm{main}}$) can be estimated by:

$$PTD_{i,\mathrm{main}} \approx \sum_{c\in \mathrm{TRM}} P_{i,c|c\in \mathrm{TRM}} + \sum_{c\in \mathrm{TOM}} P_{i,c|c\in \mathrm{TOM}} + \sum_{c\in \mathrm{CM}} P_{i,c|c\in \mathrm{CM}} \quad (4)$$

3.1.2. *Derailments in yards and terminals*

There are two types of events that can cause derailments in yards and terminals: the *arrival/departure event* for unit trains or manifest trains arriving at or departing from terminal facilities or classification yards, and the *yard switching event* associated with the sorting, switching, assembling, and dissembling processes for manifest trains in classification yards. According to Zhao and Dick (2022), A/D events are classified as either train-mile-based causes or car-mile-based causes. Thus, the probability of an A/D incident is estimated by the cause-based train derailment model. Assume that there is a manifest train with L cars (railcars only) and the manifest train transverses m intermediate classification yards with n A/D events. The relationship between n and m for manifest trains is developed in Eq. (5). Since each railcar is switched once at the origin yard and once at each intermediate yard, this manifest train has $(m+1)\times L$ car switching movements. Similarly, by definition, a unit train with L railcars (railcars only) will have two A/D events (one at the origin yard and one at the destination yard). On the other hand, the yard switching derailment probability depends on the number of cars possessed.

$$n = 1\,(\text{origin yard}) + 2\times m(\text{intermediate yard}) + 1\,(\text{destination yard}) \quad (5)$$

The probability of an A/D train derailment due to the c^{th} cause can be calculated by Eq. (6) if c is a train-mile-based cause and by Eq. (7) if c is a car-processed-based cause. If the train derailment is due to a yard switching event (for manifest trains only), Eq. (8) is used to calculate the probability of a train derailment.

$$P_{c|c\in \mathrm{ADTR}} \approx d_{\mathrm{ADTR}}/1,000,000 \times n \times p_c \quad (6)$$

$$P_{c|c\in \mathrm{ADCA}} \approx d_{\mathrm{ADCA}}/1,000,000,000 \times L \times n \times p_c \quad (7)$$

$$P_{\mathrm{YS}} \approx d_{\mathrm{YS}}/1,000,000 \times L \times (m+1) \quad (8)$$

$P_{c|c\in \mathrm{ADTR}}$: the probability that this freight consist train derails while arriving at or departing from a terminal or classification yard and the derailment is caused by a train-processed-based cause.

$P_{c|c\in \mathrm{ADCA}}$: the probability that this freight consist train derails while arriving at or departing from a terminal or classification yard and the derailment is caused by a car-processed-based cause.

P_{YS}: the probability that this yard consist train derails while switching in yards.

d_{ADTR}: the number of A/D train derailments per million train A/D events (Table 3).

d_{ADCA}: the number of A/D train derailments per billion car A/D events (Table 3).

d_{YS} : the number of yard switching derailments per million cars processed in the yard (Table 3).

p_c: the fraction of derailments of c^{th} cause in the total number of derailments while arriving at or departing from a terminal or classification yard (Table B.1 in Appendix B).

L: train length, i.e., number of railcars in the train.

n: the number of arrival/departure events that a shipment involves.

m: the number of intermediate yards that a manifest train shipment involves.

Combining risk components due to various causes, the probability of a train derailment per shipment during A/D events and during yard switching events, defined as PTD_{ADI} and PTD_{YSI}, respectively, can be approximately estimated as follows:

$$PTD_{\mathrm{ADI}} \approx \sum_{c\in \mathrm{ADTR}} P_{c|c\in \mathrm{ADTR}} + \sum_{c\in \mathrm{ADCA}} P_{c|c\in \mathrm{ADCA}} \quad (9)$$

$$PTD_{\mathrm{YSI}} \approx P_{\mathrm{YS}} \quad (10)$$

Note that the calculation of PTD_{ADI} and PTD_{YSI} can distinguish train types, yard types, and yard switching approaches by considering different derailment datasets.

3.2. *Number of railcars derailed per train derailment*

3.2.1. *Line-haul incidents on mainlines and A/D incident in yards/terminals*

Derailment severity, defined as the total number of railcars derailed given a mainline train derailment, can be affected by the point of derailment (POD), derailment speed, train type, train length (number of railcars), and average gross tonnage per car on mainlines. Since the arrival/departure process in a yard or terminal operates similarly to mainline freight operations with a reduced speed, the method for estimating the derailment severity of an A/D accident in the yard and the terminal is the same on mainlines.

Normalized by the train length (the number of railcars), the normalized POD (denoted as NPOD) can be best predicted by Beta distributions of $Beta(0.7549, 0.9582)$ for the unit train and $Beta(0.7842,$

Table 3
Derailment rates for various events, train configurations, yard types, and yard traffic metrics for the years 1996–2018 (Zhao & Dick, 2022).

	Arrival/Departure event		Yard switching event
Group	Derailments per million train arrival/departures	Derailments per million car arrival/departures	Derailments per million cars-processed in classification yards
Manifest train	61.52	1.04	6.43
Flat yard	118.92	2.02	6.38
Hump yard	36.53	0.62	6.49
Unit train	76.95	0.74	N/A
Loaded unit	126.31	1.22	N/A

1.1002) for the manifest train on mainlines using FRA train derailment data from 1996 to 2018. The "best fits" are $Beta(0.5350, 0.9121)$ and $Beta(0.7729, 0.9034)$ for the manifest train and the unit train in yards and terminals, respectively. The Beta distribution fits are consistent with findings from prior research using older datasets (Saccomanno & El-Hage, 1989, Saccomanno & El-Hage, 1991, and Liu et al., 2014).

The probability that the train derails starting from the k^{th} position (for both mainline and A/D derailments) can be calculated by (Liu et al., 2014; Liu & Schlake, 2016):

$$POD(k|TD) = F\left(\frac{k}{L}\right) - F\left(\frac{k-1}{L}\right) \tag{11}$$

TD: a train derailment, which can be a line-haul train derailment or an A/D train derailment.

$POD(k|TD)$: the probability that the POD is at the k^{th} position of a train given a train derailment.

$F(x)$: the cumulative density distribution of the corresponding fitted NPOD distribution (i.e., best fitted Beta distributions).

L : train length, i.e., number of railcars in the train.

As demonstrated by previous studies (Anderson & Barkan, 2005; Bagheri et al., 2011; Saccomanno and El-Hage, 1989; Saccomanno and El-Hage, 1991), the conditional probability of derailing x railcars given that the point of derailment is at the k^{th} position on segment i, denoted as $P_i(x|\ \text{POD} = k)$, can be estimated by the Truncated Geometric Logistic model:

$$P_i(x|\text{POD} = k) = \begin{cases} \dfrac{\dfrac{\exp(z)}{1+\exp(z)} \times \dfrac{\exp(z)}{[1+\exp(z)]^{x-1}}}{1 - \left[\dfrac{1}{1+\exp(z)}\right]^{L_r}}, & if\ x = 1, 2, \cdots L_r \\ 0, & otherwise \end{cases} \tag{12}$$

$$L_r = L - POD + 1 \tag{13}$$

where z takes different values for different derailment locations:

$$z_{\text{main}} = -0.952 - 0.0306 \times DS - 0.0018 \times L_r - 0.00239 \times GT + 0.119 \times EUT - 0.339 \times LUT \tag{14}$$

$$z_{\text{yard}} = -1.595 - 0.0029 \times L \tag{15}$$

$$z_{\text{term}} = -1.574 - 0.0016 \times L \tag{16}$$

where

$P_i(x|\ \text{POD} = k)$: the conditional probability of derailing x railcars given that the POD is at the k^{th} position on segment i.

L: train length, i.e., number of railcars in the train.

POD: point of derailment.

L_r: the number of railcars behind the point of derailment, defined in Eq. (13).

GT: average gross tonnage per car.

EUT: if the train is an empty unit train, $EUT = 1$, otherwise $EUT = 0$.

LUT: if the train is a loaded unit train, $LUT = 1$, otherwise $LUT = 0$.

On mainlines, the derailment severity can be estimated using Eqs. (12) – (14). The parameters used in Eq. (14) are from Liu et al. (2023). When building this model, the manifest train is used as a reference. Thus, for manifest trains, variables *EUT* and *LUT* in Eq. (14) are set to 0. In the yard, the derailment severity for a manifest train A/D incident is estimated by Eqs. (12), (13), and (15); in the terminal, the derailment severity for a loaded unit train A/D incident can be calculated by Eqs. (12), (13), and (16) (Zhao et al., 2022).

3.2.2. Yard switching events

While the study of arrival/departure risk in the yard/terminal can consider the same unit train and manifest train consists studied on the mainline, by definition, the yard switching process will alter the arriving manifest train consist into new departing manifest train consists heading toward the same destination yards. The yard switching process typically involves the movement of a single railcar, a cut of cars, or a portion of a train (potentially moving in reverse or as a shoving movement) at a reduced speed by a yard switching crew using a switch engine (not the mainline locomotive). Thus, the traditional definitions of a train consist and "point of derailment" described in Section 3.2.1 are not applicable, and a new risk analysis methodology for yard switching incidents must be developed.

Zhao et al. (2022) examined 89 potential distribution models and found that the generalized exponential distribution best fits the empirical FRA REA yard derailment data for the years 1996–2018. The probability mass functions (denoted as $f(x)$) of the best fitted generalized exponential distributions for yard switching events are presented in Eq. (17) for all yard types, in Eq. (18) for flat yards, and in Eq. (19) for hump yards.

$$f(x) = \left(1.44 + 1.37^{-7} \times \left(1 - e^{-1.1x}\right)\right) \times \exp^{1.44x - 1.37^{-7}x + 1.25^{-7} \times \left(1 - e^{-1.1x}\right)} \tag{17}$$

$$f(x) = (1.01 + 1.68^{-7} \times \left(1 - e^{-1.68x}\right)) \times \exp^{1.01x - 1.68^{-7}x + 1.00^{-7} \times \left(1 - e^{-1.68x}\right)} \tag{18}$$

$$f(x) = (5.05^{-8} + 2.40^{-5} \times \left(1 - e^{-3.12x}\right)) \times \exp^{5.05^{-8}x - 2.40^{-5}x + 7.70^{-6} \times \left(1 - e^{-3.12x}\right)} \tag{19}$$

This paper assumes that the derailment occurs when a cut of the group of railcars is switched together for yard switching incidents. The concept of "point of derailment" in Section 3.2.1 is defined from the perspective of root causes of the train derailment (for example, the derailment frequently happens from the head to the end of a train), while the "first car of derailment (FCD)" for yard switching incidents is defined only as a "label" referring to the first vehicle derailed in the cut of derailed vehicles. The main difference between POD and FCD is that POD is defined for a regular freight train consist, while FCD is defined for a yard switch train consist. These two terms are defined separately to emphasize that the train consist during yard switching events is not the same as on mainlines.

Empirical data indicates that manifest trains rarely derail more than 20 cars in a yard switching incident. Thus, it is necessary to truncate the generalized exponential distribution to fit the empirical data, the length of the train (number of railcars), and the known first car of derailment. The conditional probability of derailing x railcars in a yard switching incident given that the first car of the derailment is at the k^{th} position in the group of cars, denoted as $P_{\text{YardDeRail}}(x|FCD = k)$, can be calculated by:

$$P_{\text{YardDeRail}}(x|FCD=k) = \begin{cases} f(x), & \text{if } x < min(20,\ L-k+1) \\ \sum_{x=\min(20,L-k+1)}^{\infty} f(x), & \text{if } x = min(20,\ L-k+1) \end{cases} \tag{20}$$

where

FCD : the position of the first car of the derailment in the group of cars switched together.

$P_{\text{YardDeRail}}(x|FCD=k)$: the conditional probability of derailing x railcars given that the first car of the derailment is at the k^{th} position in the group of cars.

$f(x)$: the probability mass functions of the best fitted generalized exponential distributions defined in Eq. (17) for all yard types, in Eq. (18) for flat yards, and in Eq. (19) for hump yards, respectively.

L: train length, i.e., number of railcars in the train.

3.3. Number of hazmat cars releasing contents per train derailment

Different risk components (line-haul risks on mainlines, A/D risks in yards/terminals, and yard switching risks) follow different approaches to obtain the number of hazmat cars releasing contents. Before obtaining the probability distribution of the number of hazmat cars releasing contents, the analysis of line-haul risks on mainlines calculates the position-dependent releasing probability, while the analysis of A/D risks and yard switching risks estimates the probability distribution of the number of hazmat cars derailed first (see Fig. 2).

3.3.1. Line-haul events on mainlines

Based on the calculated probability distribution of the total number of railcars derailed from Section 3.2.1, we can further calculate the conditional probability of the car at j^{th} position derailing on track segment i (defined as $PD_i(j|TD)$) given a train derailment on mainlines, which is the accordance to determine the train consist. Based on previous experience and historical data, it is assumed that if a train derailment occurs, cars will derail sequentially after the POD. For example, if there are three vehicles derailed, they are POD, POD + 1, and POD + 2. According to previous work by Liu et al. (2018), $PD_i(j|TD)$ can be calculated by:

$$PD_i(j|TD) = \sum_{k=1}^{j}\left[POD(k|TD) \times \sum_{x=j-k+1}^{L_r} P_i(x|POD=k)\right] \tag{21}$$

where

TD: a train derailment.

$PD_i(j|TD)$: the conditional probability of derailing the car at j^{th} position on track segment i given a train derailment.

$POD(k|TD)$: the probability that POD is at the k^{th} position in a train given a train derailment.

$P_i(x|POD=k)$: the conditional probability of derailing x railcars given that the POD is at the k^{th} position in a train on segment i.

$\sum_{x=j-k+1}^{L_r} P_i(x|POD=k)$: the sum of the probability that the locomotive or the railcar at the j^{th} position is derailed, given that the POD is at k^{th} position.

In the next step, the position-dependent derailment probability is extended to the position-dependent tank car releasing probability, given a train derailment. Let $I_t(j)$ be the 0–1 indicator, which equals 1 if the car at j^{th} position of a train is a tank car, and 0 otherwise. We assume that the conditional probability of a derailed tank car releasing is the same given the same design and accident speed. It is also assumed that each tank car releases contents independently from others. These assumptions are made due to limited information regarding the relationship between the release probability of a derailed tank car and its position in a train. This paper calculates the probability of release (CPR) for a tank car using the results included in the RSI-AAR Tank Car Safety Project (Treichel et al., 2019).

For a car at j^{th} position of a train, the position-dependent tank car releasing probability on segment i given a train derailment, which is denoted as $R_i(j|TD)$, can be calculated as:

$$R_i(j|TD) = PD_i(j|TD) \times [I_t(j) \times CPR] \tag{22}$$

$R_i(j|TD)$: the conditional probability of releasing of the car at the j^{th} position in a train on segment i given a train derailment.

$PD_i(j|TD)$: the conditional probability of derailing the car at j^{th} position on track segment i given a train derailment.

CPR: the base conditional probability of release for a tank car with a specific tank car type developed in Treichel et al. (2019).

$I_t(j)$: the 0–1 indicator, equal to 1 if the car at the j^{th} position in a train is a tank car, and 0 otherwise.

Based on the position-dependent tank car releasing probability given a train derailment, we can further calculate the probability distribution of the number of tank cars releasing contents. Let y_j represent whether the tank car at j^{th} position releases content, which is a 0–1 variable. For each car in a train, whether a tank car would release at j^{th} position is a Bernoulli variable with releasing probability of $R_i(j|TD)$, and the probability of releasing could vary by position in a train (due to the position-dependent car derailment probability):

$$y_j \sim \ Bernoulli(R_i(j|TD)) \tag{23}$$

For the entire train, the total number of tank cars releasing contents follows a Poisson Binomial distribution, which is the sum of independent Bernoulli random variables that are not necessarily identically distributed (Chen & Liu, 1997). The Poisson Binomial distribution is used to estimate the probability associated with a certain number of releasing tank cars in a group of derailed tank cars. Let x_R be the total number of tank cars releasing contents and L be the train length. For each tank car, whether it releases is a binary event (release or no release) with release probability $R_i(j|TD)$, $\forall j$: $y_j = 1$. x_R can be mathematically expressed as Eq. (24). It follows the Poisson Binomial distribution with mean of $\sum_{j=1}^{L} R_i(j|TD)$ and variance of $\sum_{j=1}^{L} R_i(j|TD) \times (1 - R_i(j|TD))$.

$$x_R = \sum_{j=1}^{L} y_j \ \ Poisson\ Binomial\ Distribution \tag{24}$$

3.3.2. Arrival/departure events in yards/terminals

Section 3.2.1 calculates the probability that the point of derailment is at the k^{th} position in a train and the probability of derailing x railcars given the point of derailment is at the k^{th} position in a train. The probability of derailing x_{tank} tank cars given an A/D incident depends on train configuration and the placement of the block of tank cars in a manifest train, which can be calculated as:

$$P_{\text{A/DDe}}(x_{\text{tank}}|ADI) = \sum_{k=1}^{L} \sum_{\forall x: x_{\text{tank}} = \sum_{j=k}^{k+x} \delta_t(j)} POD(k|ADI) \times P_i(x|\text{POD}=k) \tag{25}$$

ADI: an arrival/departure incident in the yard/terminal.

$P_{\text{A/DDe}}(x_{\text{tank}}|ADI)$: the conditional probability of derailing x_{tank} tank cars given an A/D incident.

$\delta_t(j)$: 0–1 indicator; equals 1 if the car at the j^{th} position in the train is a tank car, and 0 otherwise.

L: train length, i.e., the number of railcars in the train.

$POD(k|ADI)$: the probability that POD is at the k^{th} position of a train given an A/D incident.

$P_i(x|\text{POD}=k)$: the conditional probability of derailing x cars given that the POD is at k^{th} position in a train on segment i.

Due to lower yard/terminal operating speeds relative to mainline speeds, the conditional probability of a tank car releasing given an A/D incident is reduced by multiplying a factor of 0.35 to reflect the fact that most of the yard/terminal accidents have lower severity and chances of release than mainline accidents in general, for which the base CPR

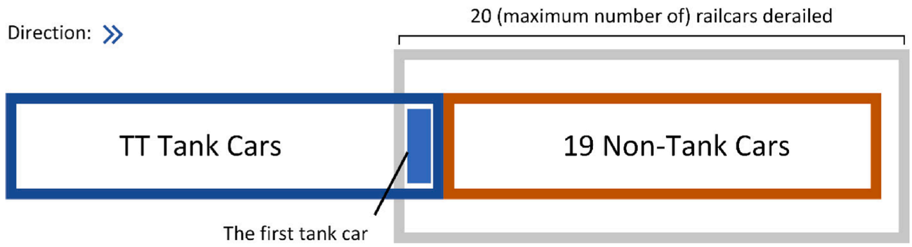

Fig. 3. Graphic explanation for the value of "19" in the "switched en masse" approach.

factors are developed (Treichel et al., 2019). Given that y tank cars derail in an A/D incident, the number of tank cars releasing contents follows a binomial distribution with y independent experiments and a success probability of $0.35 \times CPR$ for each experiment. Let $P_{A/DRe}(x_{tank}|ADI)$ denote the probability that there are x_{tank} hazmat cars releasing contents given an A/D incident in yards/terminals and TT denote the total number of tank cars in a train. Once the yard- or terminal-specific derailment rates (Section 3.1.2), the number of railcars derailed (Section 3.2.1), and the number of tank cars derailed (Eq. (25)) are determined, the conditional probability of releasing x_{tank} tank cars can be determined as follows:

$$P_{A/DRe}(x_{tank}|ADI) = \sum_{y=x_{tank}}^{TT} \binom{y}{x_{tank}} (0.35 \times CPR)^{x_{tank}} \times (1 - 0.35 \times CPR)^{y-x_{tank}} \times P_{A/DDe}(y|ADI) \tag{26}$$

where

ADI: an arrival/departure incident in the yard/terminal.

$P_{A/DRe}(x_{tank}|ADI)$: the conditional probability that there are x_{tank} hazmat cars releasing contents given an A/D incident in yards/terminals.

TT: the total number of tank cars in a train.

CPR: the base conditional probability of release developed in Treichel et al. (2019).

$P_{A/DDe}(y|ADI)$: the conditional probability that there are y hazmat cars derailed in an A/D incident.

3.3.3. Yard switching events

Zhao et al. (2022) found that calculating the number of tank cars derailed in a yard switching incident distinguishes the yard switching approaches. Accordingly, this paper assumes that tank cars are grouped as a block in yard switching events. Section 3.2.2 has explained that it is rare for manifest trains to derail more than 20 cars in a yard switching incident. Thus, in this study, the block of tank cars (no more than 20) can be analyzed either 1) as being "*switched alone*" as an independent group of TT tank cars, or 2) as being "*switched en masse*" as a block of TT tank cars behind 19 other non-hazmat cars for a total switching "cut" of $19 + TT$ railcars. The analysis considers 19 non-hazmat railcars in front of the TT tank cars because, as mentioned, the probability of derailing more than 20 railcars in a yard switching derailment is effectively zero. Assume that 20 non-tank cars followed by 20 tank cars are switched together. Within this framework, in a yard switching derailment, if the first railcar (non-tank car) of the group derails and the resulting derailment spreads back through the railcars to derail the maximum amount of 20 railcars, none of the 20 tank cars will be derailed since the final car to derail is the last non-tank car immediately in front of the first tank car in the group. In other words, when the first car to derail is more than 19 cars away from the block of TT tank cars, there will be (almost) zero chance of derailing any tank cars and the scenario can be ignored (Fig. 3). This paper considers the worst case (when there are at least 19 non-tank cars in front of the block of tank cars) from the conservative perspective for safety concerns. The total cut size of TT tank cars using the "switched alone" approach, or $19 + TT$ railcars using the "switched en masse" approach is considered to calculate the number of hazmat cars derailed in yard switching incidents.

Again, this paper assumes that the derailment occurs as a cut of the group of railcars switched together. Thus, for both the "switched alone" and "switched en masse" approaches, the probability that the first car of the derailment is at k^{th} position in the group of railcars switched together, when a yard switching incident has occurred, can be calculated as:

$$FCD(k|YSI) = \frac{1}{TCC} \tag{27}$$

where

Y: a yard switching incident.

$FCD(k|YSI)$: the probability that the first car of the derailment is at the k^{th} position in the group of cars switched together given a yard switching incident.

TCC: the total number of cars considered in a yard switching event. For the "switched alone" approach, TCC is the number of tank cars, while it is the number of tank cars plus 19 non-tank cars for the "switched en masse" approach.

For the "switched alone" approach, since all cars switched together are tank cars, the probability of derailing x_{tank} tank cars given a yard switching incident can be estimated by:

$$P_{YardDeTank}(x_{tank}|YSI) = \sum_{k=1}^{TCC-x_{tank}+1} FCD(k|YSI) \times P_{YardDeRail}(x_{tank}|FCD = k) \tag{28}$$

Where

YSI: a yard switching incident.

$P_{YardDeTank}(x_{tank}|YSI)$: the conditional probability of derailing x_{tank} tank cars given a yard switching incident.

FCD: the position of the first car of the derailment in the group of railcars.

$FCD(k|YSI)$: the probability that the first car of the derailment is at the k^{th} position in the block of tank cars given a yard switching incident.

TCC: total cars considered. For the "switched alone" approach, TCC is the number of tank cars.

$P_{YardDeRail}(x_{tank}|FCD = k)$: the conditional probability of derailing x_{tank} railcars given that the first car of the derailment is at the k^{th} position in the group of cars.

Note that in Eq. (28), k sums from 1 to $TCC - x_{tank} + 1$ since the remaining cases are not able to derail x_{tank} tank cars.

For the "switched en masse" approach, the first car derailed can be any of 19 non-tank cars or the following block of tank cars. Thus, the probability of derailing x_{tank} tank cars given a yard switching incident using the "switched en masse" approach is:

$$P_{YardDeTank}(x_{tank}|YSI) = \sum\nolimits_{k=x_{tank}}^{19} FCD(k|YSI) \times P_{YardDeRail}(20 - k + x_{tank}|FCD = k) + \sum_{k=20}^{TCC-x_{tank}+1} FCD(k|YSI) \times P_{YardDeRail}(x_{tank}|FCD = k) \tag{29}$$

where

YSI: a yard switching incident.

$P_{\text{YardDeTank}}(x_{\text{tank}}|YSI)$: the conditional probability of derailing x_{tank} tank cars given a yard switching incident.

$FCD(k|YSI)$: the probability that the first car of the derailment is at the k^{th} position in the block of tank cars given a yard switching incident.

TCC: the total number of cars considered in a yard switching event. It is the number of tank cars plus 19 non-tank cars for the "switched en masse" approach.

$P_{\text{YardDeRail}}(x_{\text{tank}}|FCD = k)$: the conditional probability of derailing x_{tank} railcars given that the first car of the derailment is at the k^{th} position in the group of cars.

In Eq. (29) the first term on the right-hand side calculates the probability of releasing x_{tank} tank cars if the first car of the derailment is a non-tank car. The expression "$20 - k + x_{\text{tank}}$", in the term $P_{\text{YardDeRail}}(20 - k + x_{\text{tank}}|FCD = k)$, comes from the situation where the first car of the derailment is at k^{th} position; the non-tank cars (from k^{th} to 19^{th} positions) and the first x_{tank} tank cars (from 20^{th} to $19 + x_{\text{tank}}$ positions) are derailing to satisfy that there are exactly x_{tank} tank cars derailing, which is the condition that there are "$19 - k + 1 + x_{\text{tank}}$" railcars derailed. The second term on the right-hand side of Eq. (29) considers all cases if the first car of the derailment is a tank car. Knowing the probability distribution of the number of tank cars derailed, the probability of releasing x_{tank} tank cars given a yard switching incident (denoted as $P_{\text{YardReTank}}(x_{\text{tank}}|YSI)$) can be estimated by the same method as Eq. (26).

3.4. Number of hazmat cars releasing contents per shipment

Sections 3.2 and 3.3 calculate conditional probabilities given a certain type of train derailment. This section removes the "conditions" in the probability distributions developed in Section 3.3 and calculates the probability of a certain number of hazmat cars releasing per shipment.

3.4.1. Line-haul incidents on mainlines

Section 3.1.1 defined the probability of a line-haul incident per shipment on the mainline segment i as $PTD_{i,\ \text{main}}$, and Section 3.3.1 found that the probability of releasing x_R tank cars on the mainline segment i per train derailment (denoted as $P_{\text{main,i,re}}(x_R|TD)$) follows a Poisson Binomial distribution. Thus, the probability of releasing x_R tank cars on the mainline segment i per shipment is:

$$P_{\text{main,i,re}}(x_R) = P_{\text{main,i,re}}(x_R|TD) \times PTD_{i,\ \text{main}} \tag{30}$$

where

$P_{\text{main,i,re}}(x_R)$: the probability of releasing x_R tank cars on the mainline segment i per shipment.

$P_{\text{main,i,re}}(x_R|TD)$: the probability of releasing x_R tank cars on the mainline segment i per train derailment.

$PTD_{i,\ \text{main}}$: the probability of a line-haul incident per shipment on the mainline segment i.

3.4.2. Unit train incidents in terminals and manifest train incidents in yards

Section 3.1.2 calculated the likelihood of a train derailment per shipment during A/D events or yard switching events (PTD_{AD} and PTD_{SWI}). To distinguish between train types (unit and manifest trains), PTD_{AD} is written as $PTD_{\text{AD,Unit}}$ and $PTD_{\text{AD,Manifest}}$ to represent the probability of a train derailment per shipment during A/D events in terminals for unit trains and in yards for manifest trains. Furthermore, Section 3.3.2 and Section 3.3.3 built the probability distributions of the number of tank cars releasing contents given an A/D incident or a yard switching incident. Based on those calculations, for a unit train, the probability of releasing x_{tank} tank cars per shipment in terminals is:

$$P_{\text{terminal}}(x_{\text{tank}}) = P_{\text{A/DRe}}(x_{\text{tank}}|ADI) \times PTD_{\text{ADI,Unit}} \tag{31}$$

where

$P_{\text{terminal}}(x_{\text{tank}})$: the probability of releasing x_{tank} tank cars per shipment for a unit train in terminals.

$P_{\text{A/DRe}}(x_{\text{tank}}|ADI)$: the conditional probability that there are x_{tank} hazmat cars releasing contents given an A/D incident in terminals.

$PTD_{\text{ADI,Unit}}$: the probability of a train derailment per shipment during A/D events in terminals using unit trains.

In contrast, for a manifest train, the probability of releasing x_{tank} tank cars per shipment in yards is:

$$\begin{aligned} &P_{\text{yard}}(x_{\text{tank}}) \\ &= P_{\text{A/DRe}}(x_{\text{tank}}|ADI) \times PTD_{\text{ADI,Manifest}} \\ &+ P_{\text{YardReTank}}(x_{\text{tank}}|YSI) \times PTD_{\text{SWI}} \end{aligned} \tag{32}$$

where

$P_{\text{yard}}(x_{\text{tank}})$: the probability of releasing x_{tank} tank cars per shipment for a manifest train in yards.

$P_{\text{A/DRe}}(x_{\text{tank}}|ADI)$: the conditional probability that there are x_{tank} hazmat cars releasing contents given an A/D incident in yards.

$PTD_{\text{ADI,Manifest}}$: the probability of a train derailment per shipment during A/D events in the yard using manifest trains.

$P_{\text{YardReTank}}(x_{\text{tank}}|YSI)$: the conditional probability that there are x_{tank} hazmat cars releasing contents given a yard switching incident.

PTD_{SWI}: the probability of a train derailment per shipment during yard switching events.

3.5. Release quantity

Using historical data from the Railway Supply Institute (RSI) and the Association of American Railroads (AAR) Tank Car Accident Database (TCAD), the RSI-AAR Railroad Tank Car Safety Research and Test Project (AAR-RSI, 2014) developed the probability distribution of release quantity from a single tank car. In this paper, the amount released from a single tank car is represented in terms of the percentage of car capacity loss based on a prior study (Treichel et al., 2019). Note that most of the non-pressure tank cars such as DOT 111 s and DOT 117 s have a gallon capacity of around 30,000-gallons. Table 4 presents the lading loss per car and the corresponding probability for a non-pressurized, 30,000-gallon tank car. This distribution is used to generate the amount released for all three types of risks on mainlines or in yards/terminals given the probability distributions of number of tank cars releasing contents derived from Section 3.5.

Due to information constraints, the assumption is made that the release quantity of a tank car is independent of other tank cars. Hence, for multiple tank cars releasing contents, the total release quantity is an aggregation of the release quantity from multiple tank car releases. To be more specific, the potential release quantity for a release incident (with a specific number of releasing tank cars) is the combination of the five levels in Table 4. Each incident with a particular number of tank cars releasing contents has a probability distribution of release quantity. Take, for example, a situation where it is known that 20 tank cars are releasing. In such a case, there are 5^{20} possible combinations of amount released, which leads to a probability distribution of the total amount of hazmat release given 20 releasing tank cars. Summing up the probability distributions of the amount released for all possible values for "the number of tank cars releasing contents," we can obtain the probability distribution of the total amount released. Let $P_{\text{re}}(x)$ denote the probability of releasing x gallons of contents in total from all releasing tank cars. The input to calculate the $P_{\text{re}}(x)$ is the probability distribution of the number of cars releasing contents and the probability distribution of release quantity for a single non-pressurized tank car. The probability distribution of the number of cars releasing contents is calculated as the conditional probability distribution of the number of cars releasing contents (Section 3.4) times the train derailment probability (Section 3.1). For example, assume that there are 20 tank cars on a manifest train, and the probability of releasing 1, 2, 3, …, 20 tank cars are all identical,

Table 4
Probability distribution of release quantity for a single non-pressurized tank car with a gallon capacity of around 30,000-gallons. (Treichel et al., 2019).

Quantity of Release (QR)	Average Quantity of Release	Lading Loss per Car (gallons)	Probability
0 %-5%	2.50 %	750	0.336
5 %-20 %	12.50 %	3,750	0.095
20 %-50 %	35.00 %	10,500	0.133
50 %-80 %	65.00 %	19,500	0.123
80 %-100 %	90.00 %	27,000	0.313

and equal to 0.05. There are two possible cases resulting in releasing 4,500 gallons: 1) there are six tank cars releasing contents and each of them releases 750 gallons; or 2) there are two tank cars releasing contents: one of them releases 750 gallons, and the other tank car releases 3,750 gallons (note: there is a factor "2" reflecting that there are two ways to designate which car is releasing 750 or 3,750 gallons). Thus, according to Table 4, the probability of releasing 4,500 gallons can be calculated by:

$$\begin{aligned} P(\text{releasing } 4,500 \text{ gallons hazmat}) &= P(\text{there are six tank cars releasing contents}) \times P(\text{a tank car releasing } 750 \text{ gallons})^6 \\ &+ P(\text{there are two tank cars releasing contents}) \times P(\text{one tank car releasing } 750 \text{ gallons}) \\ &\times P(\text{one tank car releasing } 3,750 \text{ gallons}) \times 2 = 0.05 \times 0.336^6 + 0.05 \times 0.336 \times 0.095 \times 2 = 0.0032 \end{aligned} \quad (33)$$

The probability distribution of the total amount released for this 20-tank-car example is shown in Fig. 4.

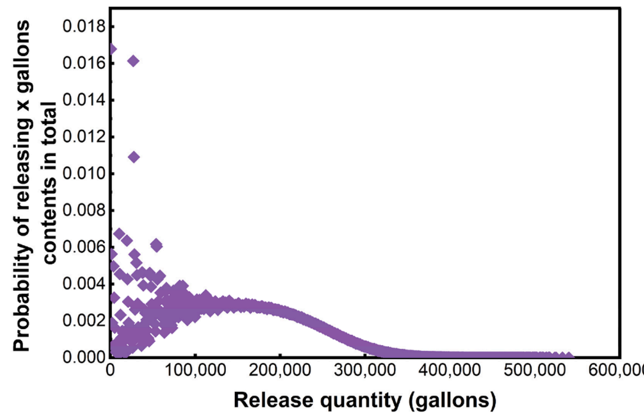

Fig. 4. Probability distribution of release quantity in gallons for the 20-tank-car example.

3.6. Releasing consequences

Performing complete consequence analyses of train operations (injuries/fatalities for all hazmat commodities, routes, etc.) is a very significant effort. Thus, this paper reduces the scope of the problem by limiting the commodities carried by tank cars to flammable liquids (crude oil and ethanol), since crude oil and ethanol combined make up a significant majority of hazmat unit train shipments. The consequence analyses performed in this section demonstrate the approach to analyzing consequences resulting from shipments on unit trains versus manifest trains. One difficulty in performing consequence analyses is that the results are often controlled by the most severe events which are extremely rare, and the methodology makes it difficult to include consequences from conditions that have not been previously observed. A consequence analysis for rail transportation of flammable liquids performed prior to 2013 would likely not have considered that an event like the Lac-Mégantic rail disaster, which resulted in 47 fatalities and more than 30 buildings destroyed, was possible. One such type of severe consequence that has not been significantly considered for flammable liquids by rail is an uncontrolled fire spread.

This paper leverages the Hazard Prediction and Assessment Capability (HPAC) with its associated analysis modules and the Nuclear Capabilities Services (NuCS) framework to assess consequences of industrial accidents (e.g., hazmat spill fires). The proposed approach applies the HPAC and NuCS toolsets to analyze a series of derailment events (flammable liquid releases) at representative real-world locations with varying population densities and various release sizes. Three representative locations along a rail line (urban, suburban, and rural) in the NuCS database are selected for the derailment sites.

The HPAC tool contains an OILSPILL model (a spreadsheet-based tool) that predicts the area and volume of contained and uncontained crude oil spills at selected locations with varying population densities and using various release sizes. The tool is geo-referenced and imports building, vegetation, and population data based on an input location. The amount of oil spilled can be estimated using railcar volumes, and this paper assumes that all fuel in the spill footprint will ignite, to be conservative. Then, the fuel spill distribution on the ground is mapped into the fuel files for the fire spread/casualty code (QUIC-FST) (Crepeau & Etheridge, 2019; Etheridge, 2020). The fire spread code is then run to provide a time-dependent map of the fuel consumed by fire, and the fire casualty model provides a time-dependent map of the casualties due to the propagating fire, with a breakdown of casualties (fatalities and injuries).

The fire spread/casualty code can be applied to a given region with a defined population to estimate fire casualties for that location and population. It calculates the probability of injury and fatality due to a thermal dose in each computational cell in the scene. Applying a random number generator and the probabilities to the population density, it estimates casualties (combined injuries and fatalities) for each computational cell. For a given spill, casualties are dependent on the vegetation and building distribution in the area.

Section 3.5 has built the probability distribution of release quantity for a unit train carrying 100 tank cars and a manifest train with a block of 20 tank cars. The results show that the probability of releasing more than 150,000 gallons of content in total is almost zero. Thus, for the consequence model in this paper, we focus on the total casualties caused by one, three, or five tank cars releasing contents, which represent small (30,000 gallons), medium (90,000 gallons), and large (150,000 gallons) sizes of tank car release incidents, respectively. By performing a series of analyses with the above tool at a series of selected locations, we can develop a set of consequence curves (Fig. 5) for casualties as a function of the time after the start of the fire event with characterization values set in Table 5.

We assume that there are no casualties when no tank cars release. Thus, we can piecewise-linearly interpolate casualties when the release quantity is between 0 and 30,000 gallons, 30,000–90,000 gallons, and 90,000–150,000 gallons. Eq. (34) is the formula to calculate expected total casualties at t minutes after the fire event (it applies to all three types of incidents).

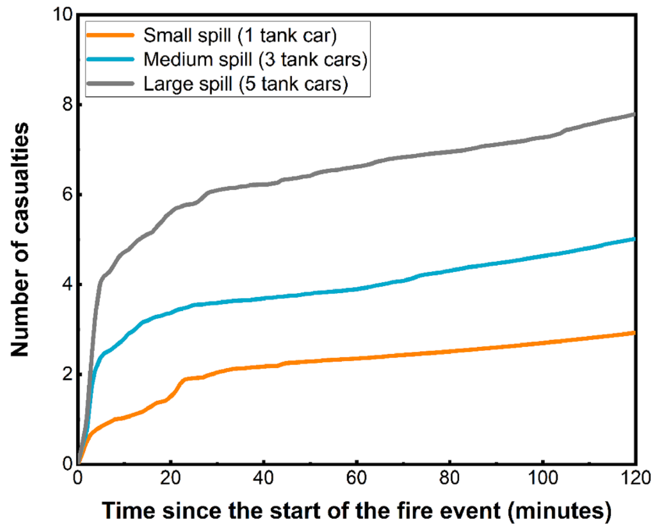

Fig. 5. Casualties from fire spread in the QUIC-FST analyses.

Table 5
Values set on calculating casualties in Fig. 5.

Route characterization	
Urban track percentage	1 %
Suburban track percentage	4 %
Rural track percentage	95 %
Weather characterization	
Low wind percentage	50 %
Medium wind percentage	49 %
High wind percentage	1 %
Evacuation time	
Nearby building evacuation time	4 mins
Maximum time since the start of the fire event	120 mins

$$TC(t) = \sum_{0<x\leq 150,000} P_{\mathrm{re}}(x) \times C(x,t) \tag{34}$$

where:

$TC(t)$: the total casualties after t minutes since the start of the fire event.

$P_{\mathrm{re}}(x)$: the probability of releasing x gallons of contents in total from all releasing tank cars (from Section 3.5).

$C(x,t)$: the expected total casualties caused by releasing x gallons of content after t minutes since the start of the fire event, and $t \in [0, 120]$ in minutes (Fig. 5).

Note that Eq. (34) applies to all three types of derailments: the line-haul train derailment, the A/D train derailment, and the yard switching train derailment. To distinguish train and derailment types, $TC(t)$ is written as $TC_{\mathrm{main,i,Unit}}(t)$ or $TC_{\mathrm{main,i,Manifest}}(t)$ to represent total casualties per shipment on the mainline segment i using a unit train or a manifest train, as $TC_{\mathrm{ADI,Unit}}(t)$ to represent total casualties per shipment during A/D events using a unit train, and as $TC_{\mathrm{Yard}}(t)$ to represent total casualties per shipment considering both A/D events and yard switching events using a manifest train.

3.7. Summary

According to the above descriptions, the total expected casualties per train derailment caused by a flammable liquid release can be calculated following the event chain described in Sections 3.1 to 3.6. Let the operator $\lceil x \rceil$ be the smallest integer greater than or equal to x. If there are δ tank cars that need to be transported, the number of shipments using unit trains (each unit train can carry c_{unit} tank cars) is $\left\lceil \frac{\delta}{c_{\mathrm{unit}}} \right\rceil$, and the total expected casualties per traffic demand (one shipment for the unit train and five shipments for the manifest train over 400 miles) can be calculated by:

$$TC_{\mathrm{Final}}(t) = \left(\sum_{\forall i} TC_{\mathrm{main,i,Unit}}(t) \times L_i + TC_{\mathrm{ADI,Unit}}(t) \right) \times \left\lceil \frac{\delta}{c_{\mathrm{unit}}} \right\rceil \tag{35}$$

where:

$TC_{\mathrm{Final}}(t)$: total casualties per traffic demand after t minutes of the fire event.

δ: the number of tank cars that need to be transported.

L_i: the length (in miles) of track segment i.

c_{unit}: the capacity of the unit train, i.e., the number of tank cars a unit train can carry.

$TC_{\mathrm{main,i,Unit}}(t)$: total casualties per shipment after t minutes of the fire event on the mainline segment i using a unit train (obtained by applying Eq. (34) in Section 3.6).

$TC_{\mathrm{ADI,Unit}}(t)$: total casualties per shipment after t minutes of the fire event during A/D events using a unit train (obtained by applying Eq. (34) in Section 3.6).

Using manifest trains (each manifest train can carry c_{manifest} tank cars) to perform the same service, the number of shipments needed is $\left\lceil \frac{\delta}{c_{\mathrm{manifest}}} \right\rceil$, and the total casualties per traffic demand can be estimated by:

$$TC_{\mathrm{Final}}(t) = \left(\sum_{\forall i} TC_{\mathrm{main,i,Manifest}}(t) \times L_i + TC_{\mathrm{Yard}}(t) \right) \times \left\lceil \frac{\delta}{c_{\mathrm{mainfest}}} \right\rceil \tag{36}$$

where:

$TC_{\mathrm{Final}}(t)$: total casualties per traffic demand after t minutes of the fire event.

δ: the number of tank cars that need to be transported.

L_i: the length (in miles) of track segment i.

c_{manifest}: the capacity of the manifest train, i.e., the number of tank cars a manifest train can carry.

$TC_{\mathrm{main,i,Manifest}}(t)$: total casualties per shipment on the mainline segment i using a manifest train (obtained by applying Eq. (34) in Section 3.6).

$TC_{\mathrm{Yard}}(t)$: total casualties per shipment during both A/D events and yard switching events using a manifest train (obtained by applying Eq. (34) in Section 3.6).

4. Case study results and discussion

The case study is inspired by an actual hazmat unit train derailment and release incident. On November 7, 2013, a southbound Alabama & Gulf Coast Railway (AGR) train was traveling from Amory, Mississippi, towards Walnut Hill, Florida, with 88 loaded hazmat tank cars, two buffer cars, and three locomotives. The case study is designed to evaluate the relative risk of making a similar crude oil shipment in a single unit train as compared to multiple manifest trains. We assume that 100 high-hazard flammable tank cars need to be transported from Amory, Mississippi, to Walnut Hill, Florida (approximately 400 miles). In general, two service options are proposed to transport these 100 tank cars to compare the risks related to each operating strategy: 1) one unit train with 100 tank cars; 2) five manifest trains, each including 80 non-tank cars and a block of 20 tank cars. Regardless of the train type (unit or manifest train), the following assumptions are made for these two operating strategies:

- Train operating speed is 25 mph on mainlines and 15 mph in terminals/yards.
- Each train has five locomotives (each weighing 212.5 tons, for this case study).

Table 6
Summary of case study scenarios.

Scenario and Code	Train type	Number of trains needed to transport 100 tank cars	Position of 20 tank car block in manifest train	Switching approach	Number of terminals or classification yards	Yard type
1 U-T	Unit train	1	N/A	N/A	1 origin 1 destination	Terminal
2 MBAF	Manifest train	5	Back of train	Alone	1 origin 1 intermediate 1 destination	Flat
3 MBAH	Manifest train	5	Back of train	Alone	1 origin 1 intermediate 1 destination	Hump
4 MMEF	Manifest train	5	Middle of train	En Masse	1 origin 1 intermediate 1 destination	Flat
5 MMEH	Manifest train	5	Middle of train	En Masse	1 origin 1 intermediate 1 destination	Hump

- Each railcar is loaded with a gross railcar weight of 143 tons (regardless of car type).
- Tank cars are all DOT 117 s.
- Each manifest train is routed through three classification yards per shipment.
- The unit train is a fixed consist from the origin terminal to the destination terminal.
- The base conditional probability of release for a DOT 117 tank car is 0.043 (Treichel et al., 2019) in this predefined context. The CPR of a tank car is affected by accident characteristics such as speed and tank car features (e.g., tank thickness and top fitting protection). The conditional probabilities of releasing vary for different types of tank cars: the CPR can be within the range from 0.041 to 0.134 for various tank car types (Treichel et al., 2019).

Five scenarios are designed in order to compare the risks associated with the operating strategies using one unit train or five manifest trains carrying 100 tank cars over 400 miles considering four different factors. *Train type* is the primary factor. Scenario 1 uses one unit train to transport all 100 tank cars, while scenarios 2–5 use five manifest trains to transport these 100 high-hazmat flammable tank cars. *Position in manifest train* is the second factor. Scenarios 2 and 3 place the block of 20 tank cars at the back of the train (i.e., positions with the lowest probability of derailment based on the position-dependent derailment probability distribution on the mainline to test the best-case scenario regarding tank car positions, which will be shown and discussed in the following calculation), while scenarios 4 and 5 place this block in the middle of the train (i.e., positions with the highest probability of derailment to test the worst-case scenario regarding tank car positions). The conditional position-dependent derailment probability distribution given a mainline train derailment will be presented in detail in Section 4.2.1. *Yard switching approach* for the manifest train is the third factor in comparing the relative effects of making different assumptions about how railcars are switched in yards. Scenarios 2 and 3 consider the block of 20 tank cars to be "switched alone," while scenarios 4 and 5 consider the block of 20 tank cars to be "switched en masse" with a group of 19 non-hazmat railcars in front (Fig. 3). The "switched alone" approach generates a lower risk compared to "switched en masse," since the switched railcar is not coupled to any non-hazmat railcars. Note that in this experiment design, the position of the tank car block in the manifest train on the mainline is correlated with the switching approach: tank cars positioned in the middle of the manifest train are "switched en masse" (worst-case scenario for manifest trains) while tank cars positioned at the back of the train are switched alone (best-case scenario for manifest trains). This correspondence reflects the practicalities of how the manifest train might be switched by backing it over a hump or switching lead upon arrival at a classification yard. *Yard type* is included as the fourth factor to compare the relative risks of hump and flat switching yards. Scenarios 2 and 4 use flat yards, while scenarios 3 and 5 use hump yards. The last three factors do not apply to scenario 1 since it involves unit train terminals instead of classification yards.

Although the methodology for line-haul risks does not include locomotives due to data limitations, in this case study, we include five locomotives for line-haul risk calculation since the mainline operations normally have a high speed and it is necessary to consider locomotives for a derailment incident. However, since train activities in yards/terminals proceed with reduced speed and the mainline locomotives are not always included (e.g., the yard switching events are hauled by a switch engine), the risk calculation in yards/terminals does not include locomotives.

Due to the complexity of the methodology itself and various factors considered in the case study, each of the five scenarios is assigned a two- or four-character code for the unit train scenario (scenario 1) or manifest train scenarios (scenarios 2–4) to help keep track of the various factor levels associated with it. Each character designates the particular level of one of the four factors. Specifically, **U-T** represents **U**nit in **T**erminal; **MBAF** represents **M**anifest, **B**ack of train, switched **A**lone, **F**lat yard type; **MBAH** represents **M**anifest, **B**ack of train, switched **A**lone, and **H**ump yard type; **MMEF** represents **M**anifest, **M**iddle of train, switched **E**n masse, **F**lat yard type; and **MMEH** represents **M**anifest, **M**iddle of train, switched **E**n masse, and **H**ump yard type. Table 6 summarizes these five scenarios and the corresponding factor levels.

Due to the large number of scenarios, we first calculate the releasing consequence (expected casualties) related to each risk component, and then combine them for each scenario considering different factor levels.

4.1. *Derailment likelihood*

4.1.1. *Derailments on mainlines*

Given the historical train derailment data on mainlines for the years 1996–2018, summarized in Section 3, we initially categorize each cause into train-mile-based, car-mile-based, and ton-mile-based cause groups (Table A.1 in Appendix A). Assume that a mainline segment i has a length of one mile. According to the methodology described in Section 3.1.1 and the shipment information described above, the line-haul train derailment probabilities per shipment on this one-mile mainline segment i for the unit train and the manifest train are 8.53E-07 and 9.54E-07, respectively (Table A.1 in Appendix A). Since transporting 100 tank cars requires one unit train or five manifest trains in the predefined context, the line-haul train derailment probabilities per traffic demand over 400 miles are $(8.53^{-07}\times 1\times 400)$ for the unit train and $(9.54^{-07}\times 5\times 400)$ for the manifest train.

4.1.2. *Derailments in yards and terminals*

Based on the analysis of all yard/terminal derailments considering A/D events for the years 1996–2018 (Zhao & Dick, 2022), the

Table 7
Proportion of yard and terminal derailments attributed to train-mile and car-mile causes by train type (1996–2018) (Zhao & Dick, 2022).

Train type	Train-mile causes	Car-mile causes
Manifest train	78.1 %	21.9 %
Unit train	62.8 %	37.2 %

proportion of derailments attributable to train-mile or car-mile causes for unit trains and manifest trains are shown in Table 7. Following Section 3.1.2, the A/D derailment likelihoods per shipment are calculated separately for the unit train in terminals (Table 8) and the manifest train in yards (Table 9). The case study calculation of the A/D derailment likelihood combines the train-mile and car-mile (or trains processed and railcars processed) A/D derailment rates introduced in Section 3.1.2 to reflect derailment causes linked to each respective metric unit. It distinguishes between yard type, with separate manifest train A/D likelihood assuming all three yards are hump classification yards (Scenarios 3 and 5) or flat switching yards (Scenarios 2 and 4). For this 400-mile/three-classification-yard case study shipment using manifest trains, the hump yards yield a lower A/D derailment likelihood as compared to flat yards (the latter is almost three times larger than the former). One possible reason to explain higher risks in flat yards than hump yards is that hump yards have dedicated tracks for arrival and departure events and separate these two switching processes, but flat yards do not distinguish between arrival and departure tracks, leading to increased chances for accidents. In this analysis framework, the position of the tank cars in the middle or back of the manifest train does not influence the A/D derailment likelihood since the block of tank cars will traverse 400 miles/three classification yards no matter where they are placed. Hence, scenarios 2 and 4 and scenarios 3 and 5 have the same A/D derailment likelihood even though they involve trains with tank cars at different positions in the train. However, the factor of position in a manifest train will be important for later calculations of derailment severity.

The probability of a yard switching derailment per shipment for the manifest train is calculated in Table 10 according to Section 3.1.2. In addition to yard type (hump or flat yards), the yard switching derailment likelihood calculation distinguishes between the yard switching approaches ("switched alone" or "switched en masse"). The case study scenarios switching in flat yards exhibit slightly lower yard switching derailment likelihoods than hump yards, and scenarios using the "switched alone" approach have a significantly lower yard switching derailment likelihood than scenarios using the "switched en masse" approach (the latter is almost two times larger than the former).

Finally, the probabilities of line-haul derailments, A/D derailments, and yard switching derailments (hump yard or flat yard) are summarized in Table 11. Overall, the derailment likelihood on a 1-mile mainline segment is three orders of magnitude less likely than an A/D derailment or yard switching derailment in terminals and yards. This is because the metric for the mainline derailment likelihood in Table 11 is "per mile per shipment," while it is "per shipment" in terminals and yards. Comparing the arrival/departure (for options with the unit train and the manifest train) and yard switching derailment likelihoods (for options with the manifest train) across all case study scenarios, the service option using the unit train or the option with the manifest train routing through hump yards consistently exhibits lower yard/terminal derailment probabilities than other service options.

4.2. Number of hazmat cars releasing contents per derailment

4.2.1. Line-haul incidents on mainlines

According to Eq. (11), the probability of the railcar at each position being the point of derailment during the line-haul process on segment i is shown in Fig. 6. Since the placement of the block of tank cars in manifest trains is a factor affecting derailment consequences, the derailment probability at each position in a manifest train is calculated following Sections 3.2.1 and 3.3.1 (Fig. 7). As can be concluded from Fig. 7, when the 20 hazmat cars are placed in the middle of the case study manifest train (train consist is shown in Fig. 8(b)), they have a higher chance of derailing during the line-haul process as compared to when they are placed at the back of the train (train consist is shown in Fig. 8(a)). For unit trains traversing the origin and destination terminals through mainlines, the position-dependent derailment probability is also calculated in Fig. 7(c). Since the unit train is only composed of tank cars, there are no alternative railcar arrangements to consider.

According to Section 3.3.1, the probability distribution of the number of hazmat cars releasing contents on a mainline segment, given a

Table 8
The probability of A/D derailment for the unit train in terminals per shipment.

Metric unit	Metric unit proportion(Table 7)	The number of trains or cars involved per A/D event	The number of A/D events involved per shipment	The number of A/D train derailments per million train A/D events (Table 3)	The A/D derailment probability for the unit train per shipment
Train-mile cause	62.8 %	1 (train)	2	126.31	2.53E-04
Car-mile cause	37.2 %	100 (cars)	2	1.22	2.44E-04
Total	62.8 % * 2.53E-04 + 37.2 %*2.44E-04=				**2.49E-04**

Table 9
The probability of A/D derailment for the manifest train in yards per shipment.

Metric unit	Metric unit proportion (Table 7)	The number of trains or cars involved per A/D event	The number of A/D events involved per shipment	The number of A/D train derailments per million train A/D events (Table 3)		The A/D derailment probability for the manifest train per shipment	
				Hump yard	Flat yard	Hump yard	Flat yard
Train-mile cause	78.1 %	1 (train)	1 (at origin yard) + 2 (at intermediate yard) + 1 (at destination yard)	36.53	118.92	1.46E-04	4.76E-04
Car-mile cause	21.9 %	100 (cars)		0.62	2.02	2.48E-04	8.08E-04
Total	Hump yard: 78.1 %*1.46E-04 + 21.90 %*2.48E-04=					**1.68E-04**	
	Flat yard: 78.1 %*4.76E-04 + 21.90 %8.08E-04=						**5.48E-04**

Table 10
The probability of yard switching derailment for the manifest train per shipment.

Yard switching approach	Number of cars involved per yard switching event	Number of yard switching events per shipment	The number of yard switching derailments per million cars processed in the yard (Table 3)		The probability of the yard switching derailment per shipment	
			Hump yard	Flat yard	Hump yard	Flat yard
Switched alone	20 tank cars	1 (at origin) and 1 (at intermediate yard)	6.49	6.38	**2.60E-04**	**2.55E-04**
Switched en masse	19 non-tank cars and 20 tank cars				**5.06E-04**	**4.98E-04**

Table 11
Summary of the derailment probabilities for the unit train and manifest train per shipment.

Derailment type	Derailment location	Yard switching approach	Train type	
			Unit train	Manifest train
Line-haul risk (per mile per shipment)	On mainline segments	–	8.53E-07	9.54E-07
Arrival/departure risk (per shipment)	In terminals	–	2.49E-04	–
	In flat yards	–	–	5.48E-04
	In hump yards	–	–	1.68E-04
Yard switching risk (per shipment)	In flat yards	Switched alone	–	2.55E-04
		Switched en masse	–	4.98E-04
	In hump yards	Switched alone	–	2.60E-04
		Switched en masse	–	5.06E-04

train derailment, is shown in Fig. 9. The probability distributions in Fig. 9 indicate that service options with manifest trains tend to have a larger probability of releasing no tank cars while unit trains have a larger probability of releasing one to two tank cars. This originates from different train consists between unit and manifest trains. A manifest train has 80 non-tank cars that can derail with no release, which accounts for a large probability of no tank cars releasing. On the contrary, since a unit train consists of five locomotives and 100 tank cars, it has a greater opportunity to derail and result in at least one tank car releasing once a train derailment occurs on a mainline segment. Cases with more than ten tank cars releasing contents are cut in Fig. 9 since they have negligible probabilities of occurring.

4.2.2. A/D incident in yards/terminals

Following Section 3.2.1, the probability distributions of POD at each position given an A/D event are plotted in Fig. 10 for manifest trains and unit trains. These fitting results indicate that the POD in a unit train skews to the front of a train, while the manifest train has a significantly smaller probability of the first few positions being the POD. The different shapes of the two cumulative distributions in Fig. 10(a and b) also demonstrate the different characteristics between the unit train and manifest train pertaining to transportation risks.

Section 3.3.2 proposes an approach to obtain the probability distribution of the number of tank cars derailed given an A/D train derailment (Fig. 11). Since the manifest train is assumed to ship 20 tank cars along with 80 non-tank cars, even if a manifest train experiences an A/D derailment in the yard, there is still a possibility that the derailed railcars are all non-tank cars. Therefore, the sum of conditional probabilities over each number of tank cars derailed is less than one for manifest trains since the higher probability of derailing zero tank cars is not plotted for clarity. For the case study scenarios using manifest trains and placing tank cars at positions with the lowest probability of derailing, 82.5 % of the A/D derailments only involve non-tank cars (i.e., zero tank cars derailed), while the value is 62.9 % for scenarios using manifest trains and placing tank cars at positions with the highest probability of derailing.

In comparison, since the unit train only contains tank cars, the case study scenarios using unit trains involve derailing at least one tank car given an A/D incident. Hence, the sum of conditional probabilities over each number of tank cars derailed per A/D derailment is exactly-one. Note that the maximum number of tank cars derailed in a manifest train is 20, and the cases that derailed more than 25 tank cars in a unit train are cut in Fig. 11 because the corresponding probabilities are almost zero.

According to Eq. (26), the conditional probability distribution of the number of tank cars releasing contents given an A/D incident can be developed in Fig. 12. Once an A/D incident occurs, unit trains have a higher likelihood of small-scale tank car release (releasing 1–2 tank cars) than manifest trains due to the larger number of tank cars (100) on the case study unit train compared to the manifest train (20 tank cars). Regardless of train type or the placement of tank cars in a manifest train, a train is less likely to release more than three tank cars during A/D events, and the probability decreases as severity increases for all scenarios.

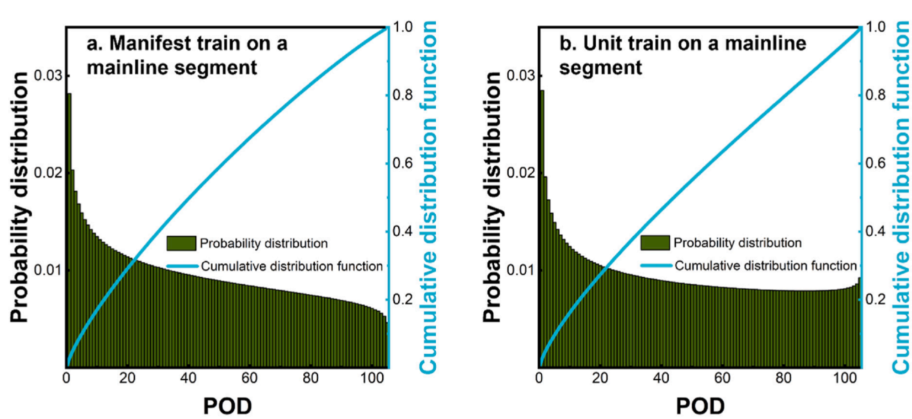

Fig. 6. Probability of railcars at each position being the point of derailment for (a) manifest train and (b) unit train on a mainline segment.

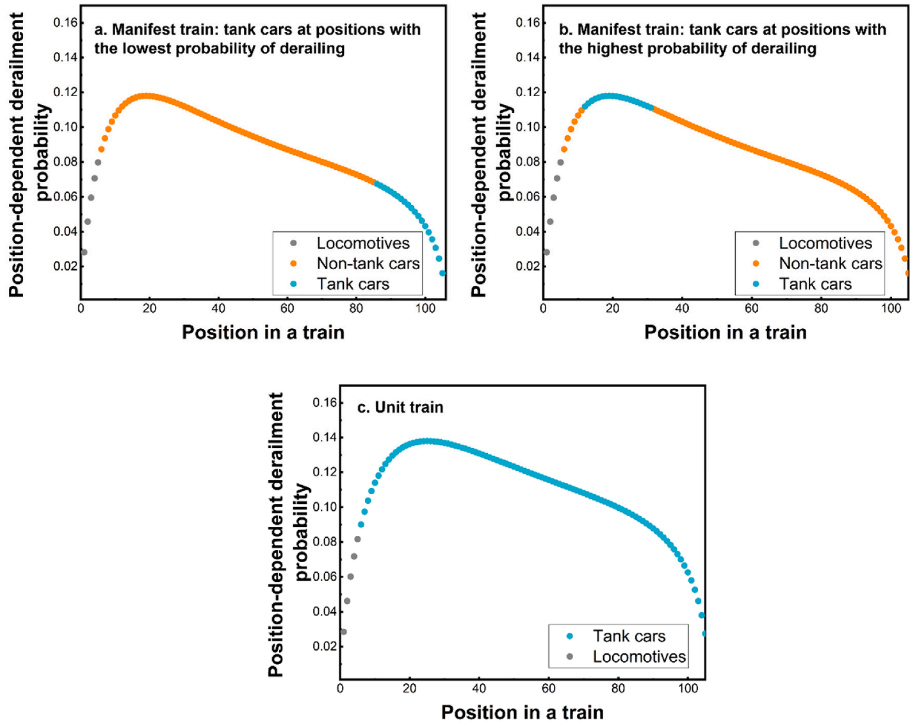

Fig. 7. Position-dependent derailment probability during line-haul transportation for (a) manifest train placing the block of tank cars at positions with the lowest derailment probability, (b) manifest train placing the block of tank cars at positions with the highest derailment probability, (c) unit train.

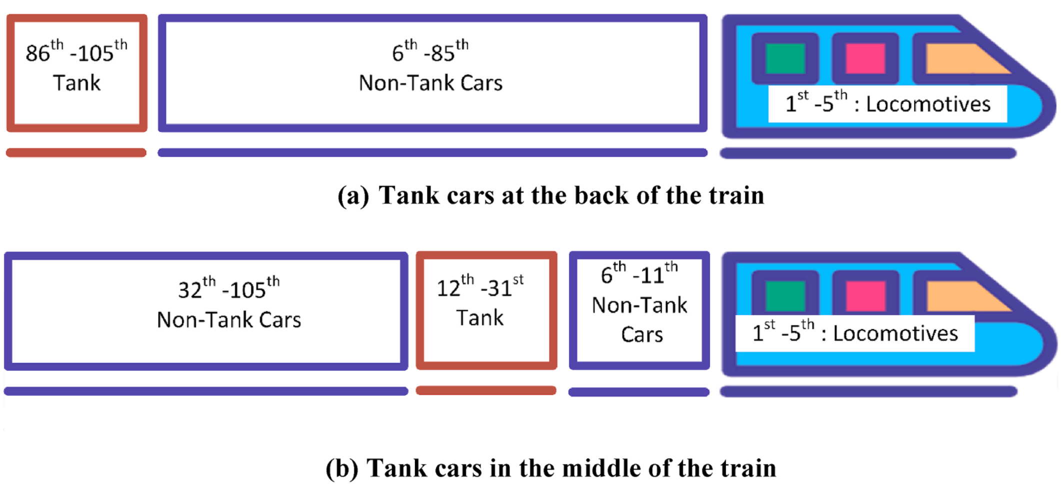

Fig. 8. Train consists of the five manifest trains (a) tank cars at the back of the train (scenarios 2 and 3), and (b) tank cars in the middle of the train (scenarios 4 and 5).

4.2.3. Yard switching incidents

Given that a yard switching derailment occurs, the conditional probability distribution of derailing x tank cars in a manifest train exhibits different characteristics depending on yard type and yard switching approach. According to Section 3.2.2, different yard types result in different derailment severities, as calculated by Eqs. (18) and (19) for flat yards and hump yards (Fig. 13). Fig. 13 indicates that derailments in flat yards, compared with those in hump yards, tend to have smaller probabilities of derailing one to two railcars but greater probabilities of derailing four to ten railcars, although the difference is very subtle.

Applying Eqs. (28) and (29), given a yard switching incident, the conditional probability distributions for the number of tank cars derailed considering different yard types and switching approaches are shown in Fig. 14. When using the "switched alone" approach, the 20 tank cars are assumed to remain in a group and be switched alone, and there is no potential impact from any other non-hazmat railcars derailing in front of and spreading to the tank cars. Given a yard switching derailment when the tank cars are switched alone, there is at least one tank car derailed. Thus, the conditional probability of derailing no tank cars given a yard switching derailment for the switched alone approach is zero for both flat and hump yards. In comparison, when the tank cars are "switched en masse" together with other non-hazmat railcars in front of them, they are exposed to additional risks created if any of the non-hazmat railcars in front of them derail and affect the tank cars. According to empirical data, as discussed in Section 3.3.3, the assumption is made that yard switching incidents derail a maximum of 20 railcars. As such, to analyze yard switching derailment severity,

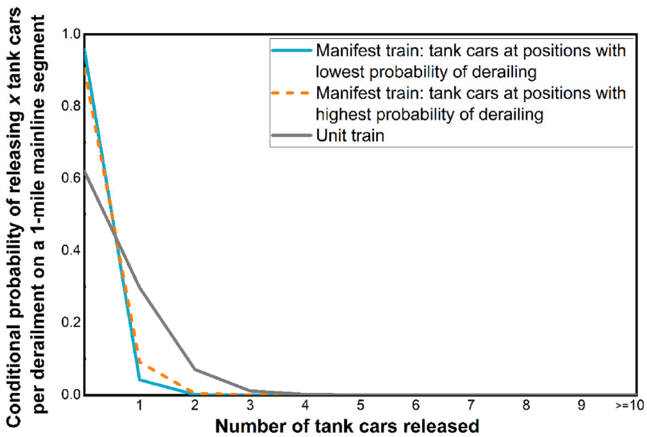

Fig. 9. Conditional probability distribution of the number of tank cars releasing contents per derailment for the line-haul incident on a 1-mile mainline segment.

service options using the "switched en masse" approach assume 19 non-tank cars followed by 20 tank cars. In this case, if the first car of a derailment is the first of the 19 non-tank cars in the group and the derailment spreads back through the railcars to a maximum amount of 20 railcars, the final car to derail will be the first of the 20 tank cars. Considering this approach, there is a possibility that a small derailment starting in the 19 non-hazmat railcars will not be large enough to spread back to the 20 tank cars. For this reason, given a yard switching derailment, the conditional probability of derailing zero tank cars is not zero (0.43 for flat yards and 0.44 for hump yards) when the case study tank cars are "switched en masse" together with non-hazmat cars.

Comparing these two yard switching approaches, considering a larger group of cars is switched (39 railcars for the "switched en masse" approach and 20 railcars for the "switched alone" approach), the base likelihood of a yard switching derailment is larger for the "switched en masse" scenarios than the "switched alone" scenarios (Table 11). However, many of the yard switching derailments that occur when switching all 39 cars together using the "switched en masse" approach involve mostly non-tank cars or relatively few tank cars. Therefore, in Fig. 14, the orange and blue lines hang above the green and purple lines. Although the "switched en masse" approach has a smaller probability of derailing one to two tank cars than the "switched alone" approach, the derailment likelihood of the former approach is twice that of the latter (Table 10). Thus, the "switched en masse" approach generates the "worst-case" scenario regarding yard switching events, while the "switched alone" approach is regarded as the "best-case" scenario.

Applying Eq. (26) with yard switching inputs, the probability distribution of the number of tank cars releasing contents given a yard switching derailment is depicted in Fig. 15. Since the conditional

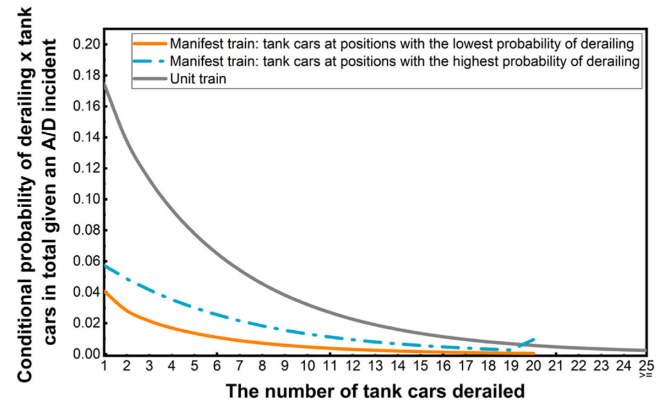

Fig. 11. Conditional probability distribution of the number of tank cars derailed given an A/D incident.

probability of release for the yard switching event is relatively low $(0.043 \times 0.35 = 0.015)$, the probability distributions in Fig. 15 skew toward the bottom left corner.

4.3. Total expected casualties per shipment

The likelihood of a train derailment per shipment considering different risk components, train types, yard types, and yard switching approaches are calculated in Section 4.1. Section 4.2 determined the conditional probability of releasing a certain number of tank cars per train derailment. Based on these results, the reverse cumulative distributions of the amount released per shipment are calculated according to

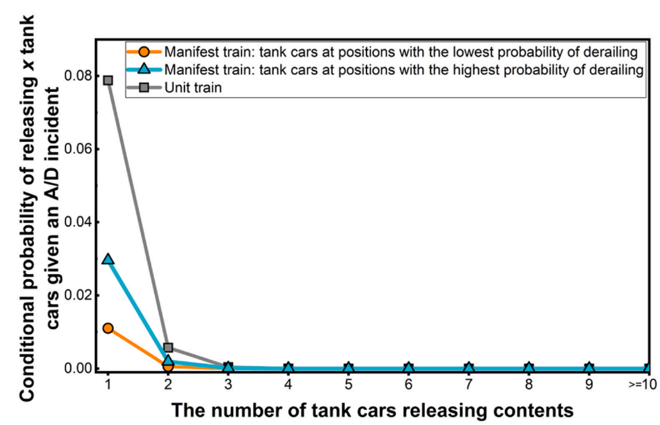

Fig. 12. Conditional probability distribution of the number of tank cars releasing contents given an A/D incident.

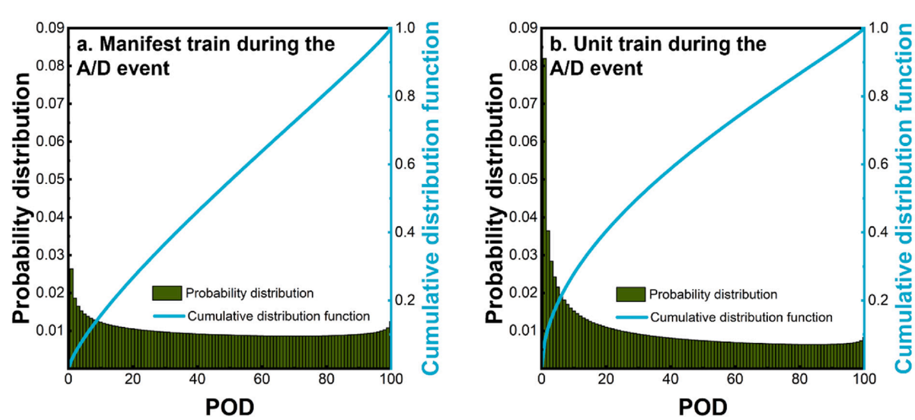

Fig. 10. Probability of railcars at each position being the point of derailment for (a) manifest train and (b) unit train during an A/D event.

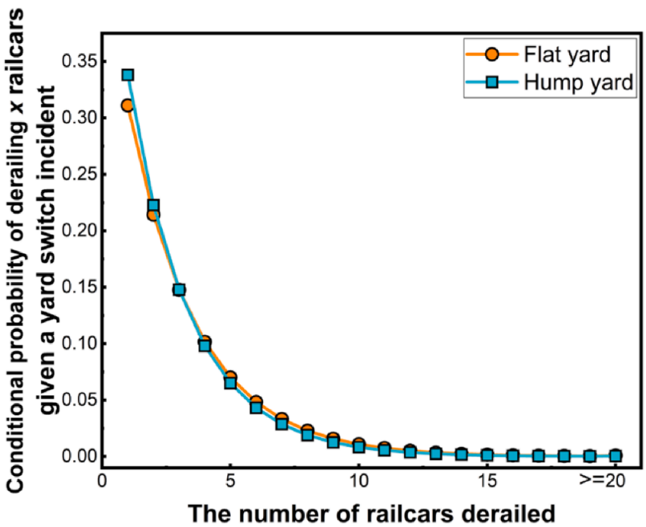

Fig. 13. The conditional probability distribution of the number of railcars derailed given a yard switching incident for different yard types.

Sections 3.4 and 3.5. The reverse cumulative distribution of the amount released details the probability distribution of releasing, in total, more than a certain number of gallons of lading contents. Fig. 16 displays the reverse cumulative distribution of the unit train and the manifest train on the mainline segment *i* (one mile). For the manifest train, the positions of tank cars play an important role in the total amount released: placing tank cars in the middle of the train has a greater probability (almost double) of releasing a certain amount of lading content compared to placing tank cars at the back of the train. Compared with the manifest train, the unit train tends to have a greater probability of releasing a certain amount of lading content on a mainline segment, no matter where the tank cars are placed in a manifest train.

Fig. 17 shows the probability distribution of the amount released for the unit train in all terminals and for the manifest trains in all classification yards for the duration of one shipment. Although the unit train does not have yard switching risks, its probability distribution of releasing a certain amount of lading content during A/D events hangs above most other service options with manifest trains. For low severity

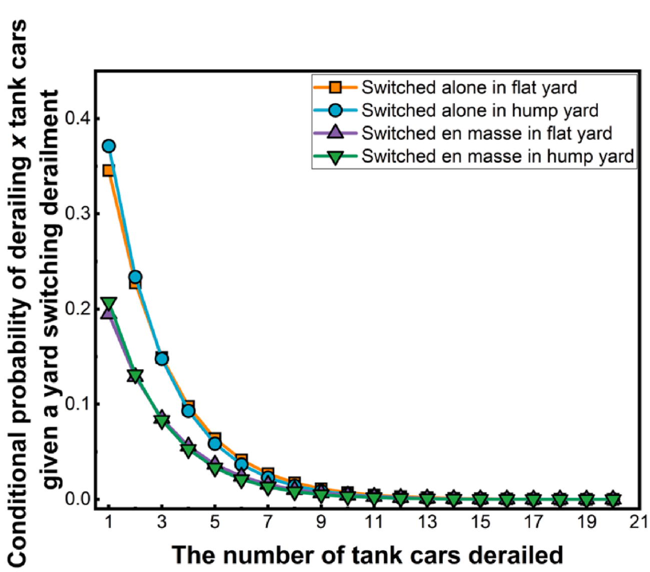

Fig. 14. The conditional probability distributions for the number of tank cars derailed considering different yard types and switching approaches given a yard switching incident.

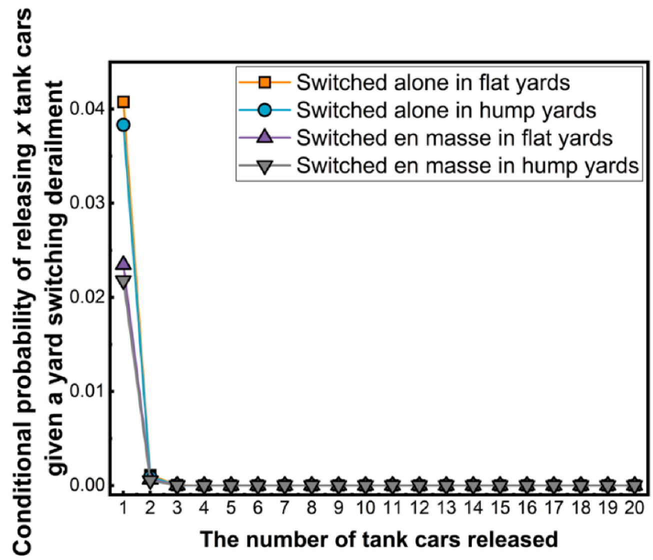

Fig. 15. Conditional probability distribution of the number of tank cars released considering different yard types and switching approaches given a yard switching derailment.

releasing incidents (releasing less than 30,000 gallons of lading contents) using manifest trains, generally, flat yards and the “switched en masse” approach exhibit higher risks compared with hump yards and the “switched alone” approach, considering the combined A/D and yard switching risks. To compare the large-scale accidents of the greatest interest in hazmat transportation risk analysis, the reverse cumulative distribution of the amount released overlaps for unit trains in terminals and manifest trains in yards when focusing on releasing more than 30,000 gallons of lading contents. Note that the reverse cumulative distributions on the mainline segment (Fig. 16) are approximately-two orders of magnitude less than in terminals or yards (Fig. 17). This is because the metric on mainline segments is “per shipment per mile,” (Fig. 16) while in terminals and yards, the metric is “per shipment (considering all terminals and yards encountered)” (Fig. 17).

This paper studies the total casualties after two hours of the fire event to represent the worst scenario. Using the probability distribution of the amount released, constructed above, and the methodology of releasing consequences described in Section 3.6, the total expected casualties per traffic demand is summarized in Table 12.

The total expected casualties per traffic demand using manifest trains

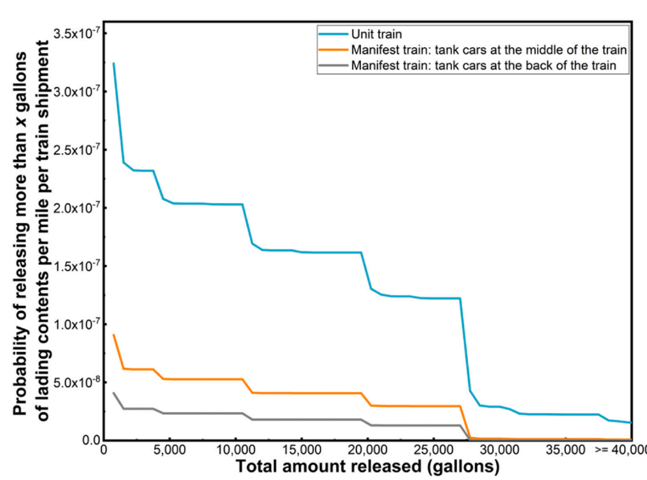

Fig. 16. The reverse cumulative distribution of the amount released per mile per shipment on the mainline segment.

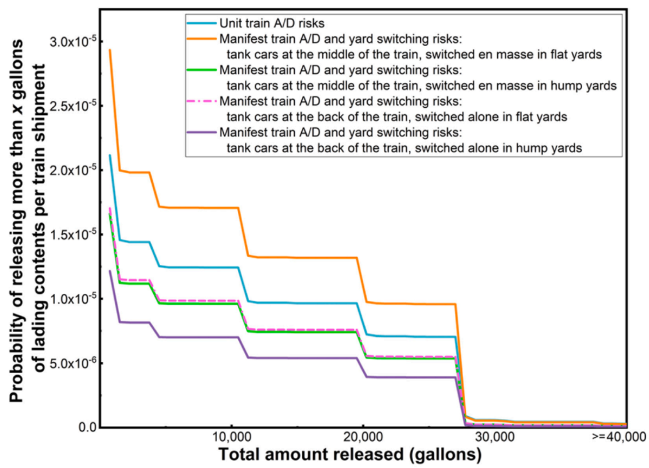

Fig. 17. The reverse cumulative distribution of the amount released per shipment in terminals (unit train) or in yards (manifest train).

Table 12
Ranking of the five scenarios concerning the total expected casualties per traffic demand.

Ranking (ascending)	Scenario and code	Expected casualties			
		Line-haul risks	Arrival/departure risks	Yard switching risks	Total per traffic demand
1	3 MBAH	1.04E-04	7.80E-05		1.82E-04
2	2 MBAF	1.04E-04	1.10E-04		2.14E-04
3	1 U-T	1.94E-04	2.81E-05	–	2.22E-04
4	5 MMEH	2.36E-04	1.07E-04		3.44E-04
5	4 MMEF	2.36E-04	1.91E-04		4.28E-04

can be compared to using unit trains. Overall, for the case study scenarios, manifest trains with tank cars in the middle of the train and switching the tank cars "en masse" with other railcars in flat yards (scenario 4) have the largest total expected casualties, followed by hump yards with tank cars in the middle and "switched en masse" (scenario 5). This result indicates that placing the tank cars at positions with the highest probability of derailing and using the "switched en masse" approach contributes the most to overall risks. The service option with one unit train carrying all 100 tank cars in one shipment (scenario 1) ranks third among all scenarios, followed by service options using manifest trains with tank cars at positions with the lowest probability of derailing and "switched alone" (scenarios 2 and 3) in classification yards. Scenario 1 tends to produce results that fall midway between scenarios 2 and 3 and scenarios 4 and 5, reflecting the importance of the tank car positions and switching approaches for manifest trains.

Comparing manifest train service options (scenarios 2 and 4 and scenarios 3 and 5) reveals that routing the case study train through flat yards will exhibit higher expected casualties than routing the case study train through hump yards due to distinct operating strategies, devices, and infrastructure. Changing the position of tank cars in manifest trains and the yard switching approaches (comparing scenarios 2 and 3 with scenarios 4 and 5) can reduce expected casualties by 50 % (for flat yards) and 47 % (for hump yards).

4.4. Sensitivity analysis by train speed

The case study described and calculated above compares the operating strategies of using one unit train or multiple manifest trains transporting 100 hazmat cars over 400 miles. All five scenarios are designed with the assumption that the train derailment speed is 25 mph on the mainline. However, train speed typically varies from 25 mph to 50 mph for mainline operations. Therefore, the sensitivity analysis is conducted for the overall risks at different speeds. The operating speeds on the mainline are set to 25 mph, 40 mph, and 50 mph for comparative purposes. All other factors remain the same. The operation speed for yards and terminals is still assumed to be 15 mph, based on the operating characteristics of railroad yards and terminals. Table 13 compares expected casualties on the mainline for different derailment speeds. The expected casualties increase with higher derailment speeds.

Table 13
Expected casualties on mainline for different derailment speeds.

Strategies	Derailment speed on the mainline		
	25 mph	40 mph	50 mph
One unit train	1.94E-04	3.95E-04	6.79E-04
The best-case train configuration with five manifest trains	1.04E-04	2.26E-04	4.37E-04
The worst-case train configuration with five manifest trains	2.36E-04	4.94E-04	8.98E-04

Fig. 18 presents the total expected casualties considering mainline risks and yard/terminal risks for various operating speeds on the mainline. The results in Fig. 18 show that the total expected casualties increase as operating speed increases, though changing the operating speed does not change the rank of each scenario as expected. However, a higher speed for the low-rank scenario (e.g., scenario 3 at 50 mph) may have higher expected casualties than a high-rank scenario with a lower speed (e.g., scenario 4 at 25 mph). This indicates that speed plays a vital role in increasing or reducing expected casualties. At a higher speed, the probability of derailment at each position increases. Once a derailment occurs, it tends to derail more tank cars than the scenarios at lower speeds.

5. Conclusions

Significant effort has been made to mitigate the risks related to rail transportation of hazardous materials due to the potentially devastating consequences. However, relatively limited prior research has compared different service options (unit trains versus manifest trains), with consideration to both mainline and yard risk components. This paper proposes a novel methodology quantifying the total risks as expected casualties for any service option, specified by train configuration, tank car placement, yard type, and switching approach. There are two or three types of risks that a unit train or manifest train encounters per shipment. A unit train experiences arrival/departure risks in terminals and line-haul risks on mainlines, while a manifest train faces additional risks during yard switching events. For each of these risks, multiple probabilistic models are built to conduct a comprehensive risk analysis for transporting hazmat by unit trains versus manifest trains. A variety of parameters are estimated for the unit train and the manifest train, separately, using historical derailment data from 1996 to 2018, considering the differences associated with various service options.

To implement the proposed methodology, this paper designs five scenarios consisting of various levels from train type, yard type, yard switching approach, and tank car placement on manifest trains. Several insights can be concluded from comparing these scenarios.

1) The placement of tank cars in each manifest train and the yard switching approach significantly affect the expected total risks. Assuming that all other contexts are the same, placing tank cars at the lowest-risk positions on a manifest train and switching tank cars

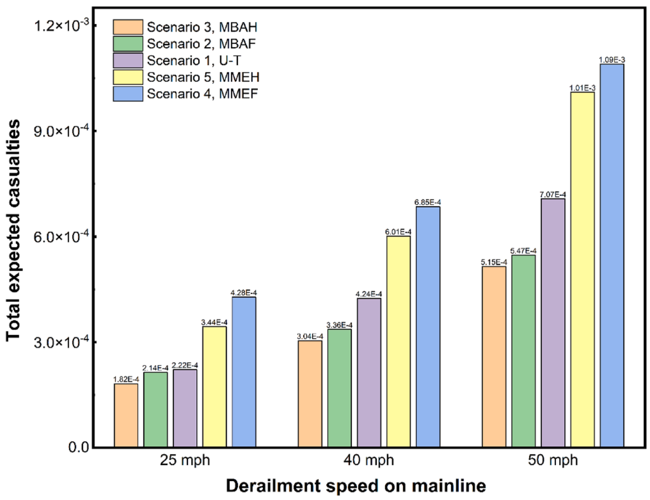

Fig. 18. Total expected casualties combining mainline risk and yard risk with various operating speeds on the mainline.

"alone" can reduce half of the total risks compared with putting them at the highest-risk positions and switching tank cars "en masse."

2) Although manifest trains encounter additional train shipments and risks during switching and sorting in classification yards, the total transportation risks also depend on tank car placement in a train, the number of yards on the route, length of the route, and other operational circumstances. Given a certain amount of hazmat to transport, choosing amongst service options should involve consideration of safety concerns, economic effects, and operational difficulties. This paper only considers the train configuration problem from a safety perspective.
3) Previous papers have generally assumed that A/D and yard switching risks in yards/terminals are small since trains in those locations operate at relatively low speeds. This paper finds that unit train operations experience a comparatively sizeable line-haul risk compared with A/D risks (the former is almost seven times larger than the latter). However, for manifest train operations, there could be a similar magnitude of risks on mainlines and in yards, given specific operating circumstances. This indicates that applying the proposed methodology could be important (especially accounting for both mainline and yard risks) when comparing unit trains and manifest trains for transporting hazardous materials.
4) According to the results from the sensitivity analysis on derailment speeds, higher speed results in higher potential risks given all else being equal.

All insights are based on predefined contexts, and this paper only considers "best" and "worst" cases from a safety perspective. There are other perspectives not considered, for example, the "best" and "worst" train configurations from economic and operational efficiency perspectives. Although the strategy involving the unit train might experience large release consequences, it has a scale effect and is easier to operate. This paper only presents a comparison between manifest trains and unit trains with the aim of minimizing release risks. A more general conclusion should be drawn considering additional perspectives.

Transporting hazmat on manifest trains might be lower risk than using unit trains in predefined contexts. Putting tank cars at the back of a train could reduce potential casualties, mainly because the position-dependent derailment probability is higher at the tail-end, given a train derailment incident. In general, some positions on a unit train have higher position-dependent derailment probabilities, but these are conditional on a train derailment incident. However, this conclusion may not hold if the contexts change. From a safety perspective only, the most important thing is to eliminate train derailments. For example, frequent inspection and maintenance would help reduce derailments caused by broken rails or welds, which is the top cause of previously recorded derailments.

In previous studies, yard risks are generally underestimated or ignored. This is the first analysis that quantifies the total risks a train may encounter throughout the shipment process, either on mainlines or in yards/terminals, distinguishing between train types. It provides a novel analytical methodology for both academia and industry practice to quantitatively evaluate the potential release consequences of transporting a certain amount of hazmat by railroad. This paper quantifies the consequences of releasing hazmat from multiple tank cars by constructing and modeling event chains for line-haul events, A/D events, and yard switching events. The case study shows the risk calculation process of transporting 100 tank cars over 400 miles. It implements the proposed methodology and demonstrates its practical value: the proposed methodology can calculate the total risks given any train configuration and generate suggestions for train consist arrangement. Train configurations and other contexts in this paper are designed according to a hazmat unit train derailment incident from 2013. The proposed methodology can be used as a tool to compare the risks associated with different operational scenarios in practice. Since there are various affecting factors when evaluating the risk of transporting hazmat by rail, for any other train configurations, the risk calculation needs to be performed for the specific context. This risk analysis methodology can be tailored to various operational characteristics.

North American freight railroads are gradually adopting the Precision Scheduled Railroads (PSR) system. PSR requires a more consistent, reliable, and predictable railroad service. It focuses on moving cars instead of trains. With PSR, trains are always moving regardless of train length. The operating strategies shift from commodity-specific unit trains to more frequent manifest trains to improve the overall service level of the network. The proposed risk model could support the operating strategy to prioritize the placement of hazmat cars to minimize the total expected release consequence for these more frequent manifest trains.

Due to data limitations, this paper assumes that the conditional probability of a derailed tank car releasing is the same given the same design and accident speed, and it also assumes that the release quantity of a tank car is independent of other tank cars. These two assumptions are made due to data or information limitations. Given more detailed data to develop the conditional probability of release in the future, a more accurate conditional probability of release could be built for each position in a train. Furthermore, sensitivity analysis could also be done for different train lengths and numbers of classification yards encountered, for particular needs. Additionally, while the risk of a loaded hazmat car derailing may be lowest when positioned at the tail-end, if there is too much tonnage in the rear portion of the train, the overall train stability will be compromised. Most railroads restrict the overall percentage of the total train tonnage permitted in the rear 25 % of the train's length. Future studies might consider the risk of derailment due to 'tail-end heavy' conditions, which usually result in stringline type derailments.

CRediT authorship contribution statement

Di Kang: Methodology, Validation, Formal analysis, Investigation, Data curation, Visualization, Writing – original draft. **Jiaxi Zhao:** Methodology, Investigation, Formal analysis. **C. Tyler Dick:** Validation, Writing – review & editing. **Xiang Liu:** Investigation, Methodology, Supervision, Project administration, Funding acquisition. **Zheyong Bian:** Validation, Writing – review & editing. **Steven W. Kirkpatrick:** Validation, Writing – review & editing. **Chen-Yu Lin:** Validation, Project administration.

Table A1
FRA-reportable Class I mainline train derailment data and the corresponding train derailment probability by cause and train type, 1996–2018.

(a) Unit train derailments

Cause group	Frequency	Percent of total	Traffic metric used	Derailment probability (one train shipment on a 1-mile segment)
Broken Rails or Welds	440	17.87	Car mile	1.53E-07
Broken Wheels (Car)	230	9.34	Car mile	7.98E-08
Bearing Failure (Car)	182	7.39	Car mile	6.32E-08
Buckled Track	152	6.17	Train mile	5.25E-08
Other Axle/ Journal Defects (Car)	152	6.17	Car mile	5.28E-08
Track Geometry (excl. Wide Gauge)	141	5.73	Train mile	4.87E-08
Obstructions	98	3.98	Train mile	3.38E-08
Wide Gauge	87	3.53	Train mile	3.00E-08
Roadbed Defects	71	2.88	Train mile	2.45E-08
Other Wheel Defects (Car)	70	2.84	Car mile	2.43E-08
Turnout Defects – Switches	65	2.64	Car mile	2.26E-08
Track-Train Interaction	58	2.36	Car mile	2.01E-08
Other Miscellaneous	56	2.27	Train mile	1.93E-08
Misc. Track and Structure Defects	50	2.03	Train mile	1.73E-08
Lading Problems	46	1.87	Car mile	1.60E-08
Joint Bar Defects	46	1.87	Car mile	1.60E-08
Coupler Defects (Car)	41	1.67	Car mile	1.42E-08
Other Rail and Joint Defects	40	1.62	Car mile	1.39E-08
Use of Switches	38	1.54	Train mile	1.31E-08
Sidebearing, Suspension Defects (Car)	36	1.46	Car mile	1.25E-08
Train Handling (excl. Brakes)	32	1.3	Train mile	1.10E-08
Non-Traffic, Weather Causes	31	1.26	Train mile	1.07E-08
Rail Defects at Bolted Joint	30	1.22	Car mile	1.04E-08
Train Speed	28	1.14	Train mile	9.67E-09
Truck Structure Defects (Car)	27	1.1	Car mile	9.37E-09
Centerplate/ Carbody Defects (Car)	22	0.89	Car mile	7.64E-09
All Other Car Defects	22	0.89	Train mile	7.60E-09
Misc. Human Factors	21	0.85	Train mile	7.25E-09
Stiff Truck (Car)	15	0.61	Train mile	5.18E-09
Switching Rules	15	0.61	Train mile	5.18E-09
Failure to Obey/ Display Signals	14	0.57	Train mile	4.83E-09
Other Brake Defect (Car)	14	0.57	Car mile	4.86E-09
Handbrake Operations	12	0.49	Train mile	4.14E-09
Brake Rigging Defect (Car)	12	0.49	Car mile	4.17E-09
Loco Electrical and Fires	11	0.45	Train mile	3.80E-09
Track/Train Interaction (Hunting) (Car)	10	0.41	Car mile	3.47E-09
Brake Operation (Main Line)	9	0.37	Car mile	3.12E-09
Mainline Rules	9	0.37	Train mile	3.11E-09
Signal Failures	8	0.32	Car mile	2.78E-09
Loco Trucks/ Bearings/ Wheels	8	0.32	Car mile	2.78E-09
Turnout Defects – Frogs	5	0.2	Car mile	1.74E-09
All Other Locomotive Defects	3	0.12	Train mile	1.04E-09
Brake Operations (Other)	2	0.08	Train mile	6.90E-10
UDE (Car or Loco)	1	0.04	Car mile	3.47E-10
Employee Physical Condition	1	0.04	Train mile	3.45E-10
Air Hose Defect (Car)	1	0.04	Car mile	3.47E-10
Total	**2,462**	**100**		**8.53E-07**

(b) Manifest train derailments

Cause group	Frequency	Percent of total	Traffic metric used	Derailment probability (one train shipment on a 1-mile segment)
Broken Rails or Welds	639	11.59	Car mile	1.39E-07
Track Geometry (excl. Wide Gauge)	391	7.09	Train mile	4.75E-08
Bearing Failure (Car)	343	6.22	Car mile	7.44E-08
Train Handling (excl. Brakes)	324	5.88	Train mile	3.94E-08
Obstructions	243	4.41	Train mile	2.95E-08
Track-Train Interaction	212	3.84	Car mile	4.60E-08
Lading Problems	211	3.83	Car mile	4.58E-08
Wide Gauge	186	3.37	Train mile	2.26E-08
Coupler Defects (Car)	184	3.34	Car mile	3.99E-08
Use of Switches	182	3.3	Train mile	2.21E-08
Broken Wheels (Car)	173	3.14	Car mile	3.75E-08
Sidebearing, Suspension Defects (Car)	164	2.97	Car mile	3.56E-08
Other Wheel Defects (Car)	164	2.97	Car mile	3.56E-08
Brake Operation (Main Line)	163	2.96	Car mile	3.54E-08
Centerplate/ Carbody Defects (Car)	148	2.68	Car mile	3.21E-08
Buckled Track	147	2.67	Train mile	1.79E-08
Other Miscellaneous	145	2.63	Train mile	1.76E-08

(continued on next page)

Table A1 (*continued*)

(b) Manifest train derailments

Cause group	Frequency	Percent of total	Traffic metric used	Derailment probability (one train shipment on a 1-mile segment)
Turnout Defects – Switches	142	2.58	Train mile	1.73E-08
Misc. Track and Structure Defects	98	1.78	Train mile	1.19E-08
Train Speed	94	1.7	Train mile	1.14E-08
Stiff Truck (Car)	85	1.54	Train mile	1.03E-08
Roadbed Defects	82	1.49	Train mile	9.96E-09
Joint Bar Defects	70	1.27	Car mile	1.52E-08
Other Axle/Journal Defects (Car)	64	1.16	Car mile	1.39E-08
Other Brake Defect (Car)	64	1.16	Car mile	1.39E-08
Loco Trucks/ Bearings/Wheels	63	1.14	Car mile	1.37E-08
All Other Car Defects	62	1.12	Train mile	7.53E-09
Track/Train Interaction (Hunting) (Car)	58	1.05	Car mile	1.26E-08
Misc. Human Factors	58	1.05	Train mile	7.05E-09
Switching Rules	55	1	Train mile	6.68E-09
Other Rail and Joint Defects	51	0.92	Car mile	1.11E-08
Rail Defects at Bolted Joint	51	0.92	Car mile	1.11E-08
Handbrake Operations	49	0.89	Train mile	5.95E-09
Non-Traffic, Weather Causes	44	0.8	Train mile	5.35E-09
Failure to Obey/ Display Signals	39	0.71	Train mile	4.74E-09
Brake Rigging Defect (Car)	35	0.63	Car mile	7.59E-09
All Other Locomotive Defects	35	0.63	Train mile	4.25E-09
Signal Failures	35	0.63	Car mile	7.59E-09
Air Hose Defect (Car)	33	0.6	Car mile	7.16E-09
Truck Structure Defects (Car)	25	0.45	Car mile	5.42E-09
Loco Electrical and Fires	23	0.42	Train mile	2.79E-09
Mainline Rules	23	0.42	Train mile	2.79E-09
Turnout Defects – Frogs	20	0.36	Car mile	4.34E-09
Radio Communications Error	12	0.22	Train mile	1.46E-09
UDE (Car or Loco)	10	0.18	Car mile	2.17E-09
Brake Operations (Other)	6	0.11	Train mile	7.29E-10
TOFC/COFC Defects	5	0.09	Train mile	6.08E-10
Employee Physical Condition	2	0.04	Train mile	2.43E-10
Handbrake Defects (Car)	2	0.04	Train mile	2.43E-10
Total	**5,514**	**100**		**9.54E-07**

Table B1
FRA-reportable Class I yard train arrival/departure event derailment data, 1996–2018 (Zhao & Dick, 2022).

(a) Unit train derailments

Cause group	Frequency	Percent of total
Broken rails or welds	224	26.79
Wide gauge	106	12.68
Turnout defects: switches	105	12.56
Use of switches	79	9.45
Switching rules	42	5.02
Miscellaneous track and structure defects	29	3.47
Track geometry (excluding wide gauge)	27	3.23
Other miscellaneous	26	3.11
Other wheel defects (car)	19	2.27
Roadbed defects	18	2.15
Rail defects at bolted joint	13	1.56
Train handling (excluding brakes)	13	1.56
Train speed	12	1.44
Stiff truck (car)	12	1.44
Lading problems	11	1.32
Other rail and joint defects	10	1.20
Track–train interaction	9	1.08
Side bearing and suspension defects (car)	8	0.96
Miscellaneous human factors	8	0.96
Handbrake operations	7	0.84
Joint bar defects	7	0.84
Buckled track	6	0.72
Signal failures	5	0.60
Nontraffic, weather causes	5	0.60
Brake rigging defect (car)	4	0.48
Failure to obey or display signals	3	0.36
Locomotive trucks, bearings, and wheels	3	0.36
All other locomotive defects	3	0.36
All other car defects	3	0.36
Brake operation (main line)	2	0.24
Centerplate or car body defects (car)	2	0.24
Extreme weather	2	0.24
Bearing failure (car)	2	0.24
Turnout defects: frogs	2	0.24
Broken wheels (car)	2	0.24
Locomotive electrical and fires	2	0.24
Handbrake defects (car)	1	0.12
Brake operations (other)	1	0.12
UDE (car or locomotive)	1	0.12
Other brake defect (car)	1	0.12
Mainline rules	1	0.12
Total	836	100

(b) Manifest train derailments

Cause group	Frequency	Percent of total
Switching rules	908	15.45
Use of switches	766	13.03
Broken rails or welds	685	11.66
Wide gauge	625	10.63
Turnout defects: switches	486	8.27
Train handling (excluding brakes)	407	6.93
Other miscellaneous	206	3.51
Handbrake operations	195	3.32
Train speed	183	3.11
Miscellaneous track and structure defects	155	2.64
Track–train interaction	150	2.55
Track geometry (excluding wide gauge)	141	2.40
Brake operation (main line)	136	2.31
Lading problems	79	1.34
Other wheel defects (car)	70	1.19
Signal failures	63	1.07
Side bearing and suspension defects (car)	59	1.00
Coupler defects (car)	56	0.95
Stiff truck (car)	54	0.92
Roadbed defects	51	0.87
Radio communications error	48	0.82
Rail defects at bolted joint	37	0.63
Miscellaneous human factors	37	0.63
Centerplate or car body defects (car)	28	0.48
Turnout defects: frogs	28	0.48
Mainline rules	26	0.44

(*continued on next page*)

Table B1 (*continued*)

(b) Manifest train derailments

Cause group	Frequency	Percent of total
Nontraffic, weather causes	22	0.37
All other car defects	18	0.31
Other rail and joint defects	16	0.27
Brake operations (other)	15	0.26
Other brake defect (car)	15	0.26
Brake rigging defect (car)	14	0.24
Extreme weather	13	0.22
Locomotive trucks, bearings, and wheels	12	0.20
All other locomotive defects	12	0.20
Buckled track	11	0.19
Failure to obey or display signals	10	0.17
Joint bar defects	10	0.17
Broken wheels (car)	8	0.14
Obstructions	4	0.07
Handbrake defects (car)	4	0.07
Employee physical condition	4	0.07
Truck structure defects (car)	4	0.07
Air hose defect (car)	2	0.03
UDE (car or locomotive)	1	0.02
Bearing failure (car)	1	0.02
Locomotive electrical and fires	1	0.02
Track–train interaction (hunting) (car)	1	0.02
Total	5,877	100

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

The data that has been used is confidential.

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Appendix A

(See Table A1).

Appendix B

(See Table B1).

References

AAR-RSI. (2014). *Preliminary distributions of quantities lost from tank cars releasing lading in accidents.*

Anderson, R.T., 2005. Quantitative analysis of factors affecting railroad accident probability and severity. University of Illinois at Urbana-Champaign [M.S. Thesis].

Anderson, R. T., & Barkan, C. P. (2005). Derailment probability analysis and modeling of mainline freight trains. *Proc., 8th International Heavy Haul Railway Conference*.

Anderson, R.T., Barkan, C.P., 2004. Railroad accident rates for use in transportation risk analysis. Transportation Research Record 1863 (1), 88–98.

Arthur D. Little, Inc. (ADL). (1996). *Risk assessment for the transportation of hazardous materials by rail, supplementary report: Railroad accident rate and risk reduction option effectiveness analysis and data.*

Bagheri, M., Saccomanno, F., Chenouri, S., Fu, L., 2011. Reducing the threat of in-transit derailments involving dangerous goods through effective placement along the train consist. Accident Analysis & Prevention 43 (3), 613–620.

Bagheri, M., Saccomanno, F., Fu, L., 2012. Modeling hazardous materials risks for different train make-up plans. Transportation Research Part E: Logistics and Transportation Review 48 (5), 907–918.

Bagheri, M., Verma, M., Verter, V., 2014. Transport mode selection for toxic gases: Rail or road? Risk Analysis 34 (1), 168–186.

Bagheri, M. (2010). *Risk-based model for effective marshalling of dangerous goods railway cars*.

Barkan, C.P., Dick, C.T., Anderson, R., 2003. Railroad derailment factors affecting hazardous materials transportation risk. Transportation Research Record 1825 (1), 64–74.

Bing, A., Dizon, A., Brickett, J., Papson, A., O'Rourke, L., Hamilton, B.A., 2015. Risk evaluation framework and selected metrics for tank cars carrying hazardous materials. United States. Federal Railroad Administration, Office of Research and Development.

Center for Chemical Process, 1995. 1995. Guidelines for chemical transportation risk analysis. American Institute of Chemical Engineers, New York.

Chen, S.X., Liu, J.S., 1997. Statistical applications of the Poisson-binomial and conditional Bernoulli distributions. Statistica Sinica 875–892.

Christou, M.D., 1999. Analysis and control of major accidents from the intermediate temporary storage of dangerous substances in marshalling yards and port areas. Journal of Loss Prevention in the Process Industries 12 (1), 109–119.

Crepeau, J., & Etheridge, M. (2019). Nuclear Capability Services, Quic-FST Verification and Validation (V&V) Report. *Defense Threat Reduction Agency (DTRA) Technical Report, Version 1*. July 12, 2019.

Dick, C.T., Zhao, J., Liu, X., Kirkpatrick, S.W., 2021. Quantifying Recent Trends in Class 1 Freight Railroad Train Length and Weight by Train Type. Transportation Research Record: Journal of the Transportation Research Board 03611981211031534.

Etheridge, M. (2020). Nuclear Capability Services, Quick Urban and Industrial Complex (QUIC)—Fire Smoke Thermal (FST) Methodology Report. *Defense Threat Reduction Agency (DTRA) Technical Report, Version 4*. June 2020.

Federal Railroad Administration. (2005). *Safe Placement of Train Cars: A Report*.

FRA. (2011). *Railroad safety statistics-preliminary annual report.*

FRA. (2012). *FRA guide for preparing accident/incident reports*.

Glickman, T.S., Erkut, E., 2007. Assessment of hazardous material risks for rail yard safety. Safety Science 45 (7), 813–822. https://doi.org/10.1016/j.ssci.2006.09.004.

Kawprasert, A., Barkan, C.P., 2010. Effect of train speed on risk analysis of transporting hazardous materials by rail. Transportation Research Record 2159 (1), 59–68.

Liu, X., 2015. Statistical temporal analysis of freight train derailment rates in the United States: 2000 to 2012. Transportation Research Record: Journal of the Transportation Research Board 2476 (1), 119–125. https://doi.org/10.3141/2476-16.

Liu, X., 2016. Collision risk analysis of freight trains in the United States. Transportation Research Record: Journal of the Transportation Research Board 2546, 121–128.

Liu, X., 2017a. Risk comparison of transporting hazardous materials in unit trains versus mixed trains. Transportation Research Record: Journal of the Transportation Research Board 2608 (1), 134–142.

Liu, X., 2017b. Statistical causal analysis of freight-train derailments in the United States. Journal of Transportation Engineering, Part A: Systems 143 (2), 04016007.

Liu, X., Kang, D., Dick, C.T., Kirkpatrick, S., Zhao, J., Bian, Z., Lin, C.-Y., Zhang, Z., 2023. Risk analysis methodology for hazardous material transportation in unit and manifest trains. Technical Report. Federal Railroad Administration (forthcoming).

Liu, X., Saat, M.R., Barkan, C.P., 2012. Analysis of causes of major train derailment and their effect on accident rates. Transportation Research Record: Journal of the Transportation Research Board 2289 (1), 154–163.

Liu, X., Saat, M.R., Qin, X., Barkan, C.P., 2013. Analysis of US freight-train derailment severity using zero-truncated negative binomial regression and quantile regression. Accident Analysis & Prevention 59, 87–93.

Liu, X., Saat, M.R., Barkan, C.P., 2014. Probability analysis of multiple-tank-car release incidents in railway hazardous materials transportation. Journal of Hazardous Materials 276, 442–451.

Liu, X., Schlake, B.W., 2016. Probabilistic analysis of the release of liquefied natural gas (LNG) tenders due to freight-train derailments. Transportation Research Part C: Emerging Technologies 72, 77–92.

Liu, X., Turla, T., Zhang, Z., 2018. Accident-cause-specific risk analysis of rail transport of hazardous materials. Transportation Research Record: Journal of the Transportation Research Board 2672 (10), 176–187.

Nayak, P.R., Rosenfield, D.B., Hagopian, J.H., 1983. Event probabilities and impact zones for hazardous materials accidents on railroads. United States, Federal Railroad Administration.

Prabhakaran, A., & Booth, G. (2018). *Objective evaluation of risk reduction from tank car design and operations improvements–extended study.*

Purdy, G., Campbell, H.S., Grint, G.C., Smith, L.M., 1988. An analysis of the risks arising from the transport of liquefied gases in Great Britain. Journal of Hazardous Materials 20, 335–355.

Saat, M.R., Barkan, C.P., 2011. Generalized railway tank car safety design optimization for hazardous materials transport: Addressing the trade-off between transportation efficiency and safety. Journal of Hazardous Materials 189 (1–2), 62–68.

Saat, M.R., Werth, C.J., Schaeffer, D., Yoon, H., Barkan, C.P., 2014. Environmental risk analysis of hazardous material rail transportation. Journal of Hazardous Materials 264, 560–569.

Saccomanno, F.F., El-Hage, S., 1989. Minimizing derailments of railcars carrying dangerous commodities through effective marshaling strategies. Transportation Research Record 1245 (34–51), 39–41.

Saccomanno, F.F., El-Hage, S.M., 1991. Establishing derailment profiles by position for corridor shipments of dangerous goods. Canadian Journal of Civil Engineering 18 (1), 67–75.

Schafer, D.H., Barkan, C.P., 2008. Relationship between train length and accident causes and rates. Transportation Research Record 2043 (1), 73–82.

Treichel, T., Ghosh, L., Saat, M.R., Barkan, C.P., Liu, X., Kirkpatrick, S., Song, J., Zhou, X., 2019. Conditional probability of release (CPR) estimates for railroad tank cars in accidents. RSI-AAR Railroad Tank Car Safety Research and. Test Project Report RA-19-01.

Zhang, Z., Lin, C.-Y., Liu, X., Bian, Z., Dick, C. T., Zhao, J., & Kirkpatrick, S. (2021). *An empirical analysis of freight train derailment rates for unit trains and manifest trains.*

Zhao, J., Dick, C.T., 2022. Quantitative Derailment Rate Comparison of Unit Trains at Transload Terminals and Manifest Trains at Railroad Switching and Hump Classification Yards. Transportation Research Record: Journal of the Transportation Research Board.

Zhao, J., Dick, C.T., Kang, D., 2022. Analysis of Derailment Severity Comparing Unit Trains at Transload Terminals and Manifest Trains at Railroad Switching and Hump Classification Yards. Transportation Research Record 03611981221137593.