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An Empirical analysis of freight train derailment rates for unit trains and manifest trains

Zhipeng Zhang[1,2], Chen-Yu Lin[3], Xiang Liu[2], Zheyong Bian[4], C Tyler Dick[5], Jiaxi Zhao[2] and Steven Kirkpatrick[2]

Abstract
Rail is a safe and efficient mode of transporting hazardous materials (hazmat). In the past decade, the hazmat traffic transported by unit trains has significantly increased in the United States. As a result, a comprehensive understanding of the safety and risk of hazmat unit trains is important and can contribute to the identification, evaluation, and implementation of risk mitigation strategies. Limited prior research has focused on unit train derailment risk analysis. This paper develops a quantitative analysis of freight unit train derailment characteristics and compares those statistics to non-unit, manifest trains (mixed trains). Mainline freight train derailment data on Class I railroads between 1996 and 2018 were analyzed for hazmat unit trains, non-hazmat unit trains, and manifest trains. Derailment rates, measured by three traffic exposure metrics (train-miles, ton-miles, and car-miles) were estimated and compared. The analyses showed that a unit train has a 30% lower derailment rate in terms of ton-miles and car-miles than manifest trains, while the derailment rate per million train-miles of unit trains is slightly greater than that of manifest trains. Loaded unit trains have roughly four-fold higher derailment rate in terms of train-miles and car-miles than that of empty unit trains. Within loaded unit trains, hazmat unit trains have lower derailment rates than non-hazmat unit trains. Overall, heavier and shorter loaded unit trains tend to have greater derailment rates in terms of all three traffic exposure metrics. A causal analysis was also conducted for the three types of train. Infrastructure causes were the most frequent in all train types and length followed by equipment-related causes. These statistics provided important information for rational allocation of risk mitigation resources to improve rail hazmat transportation safety.

Keywords
Freight train, derailment rate, unit train, safety comparison, hazmat transportation

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Introduction

Manifest trains and unit trains are two major train types operating in the United States' (US) railroad network. Manifest train (also called mixed train) are composed of mixed types of rail cars (boxcars, tank cars, hopper cars, etc.) that may be empty or carrying different types of goods for multiple shippers. This train type is primarily used to economically transport products from multiple origins to destinations by aggregating smaller groups of railcars together in a single train (UP, 2020). By comparison, a unit train is made up of a single type of railcar transporting the same commodity from one location to the same destination.

Unit trains provide economical and efficient transportation of products by reducing operating expenses, using bulk loading, improving asset utilization, and creating economies of scale (Starr, 1976; Kenkel et al., 2004; Li et al., 2018; Dick et al., 2021). For example, Kenkel et al. (2004) conducted a profitability analysis of a 100-car unit train showing that savings from unit train transportation for agricultural products generally range from $0.05 to $0.15 per bushel. Initially, unit trains were mostly used to carry coal, grain, and other forms of bulk cargo. In recent years, increasing amounts of hazardous materials (hazmat) are transported by unit trains (Li et al., 2018). Large volumes of hazmat (e.g., crude oil and ethanol) can be shipped by unit trains of 100 tank cars or even longer.

Based on an analysis of the public waybill data for the years 1996–2018 from the US Surface Transportation Board (STB, 2020a), it was found that unit trains had been

[1]State Key Laboratory of Ocean Engineering, School of Naval Architecture, Ocean and Civil Engineering, Shanghai Jiao Tong University, China
[2]Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, New Jersey
[3]Rail Transportation and Engineering Center–RailTEC, Department of Civil and Environmental Engineering, University of Illinois at Urbana-Champaign, Urbana, IL, USA
[4]Department of Construction Management, University of Houston, Houston, TX, USA
[5]Applied Research Associates, Inc, Albuquerque, USA

Corresponding author:
Xiang Liu, Department of Civil and Environmental Engineering, Rutgers, The State University of New Jersey, CoRE 606, 96 Frelinghuysen Road, Piscataway, NJ 08854-8018, USA.
Email: xiang.liu@rutgers.edu

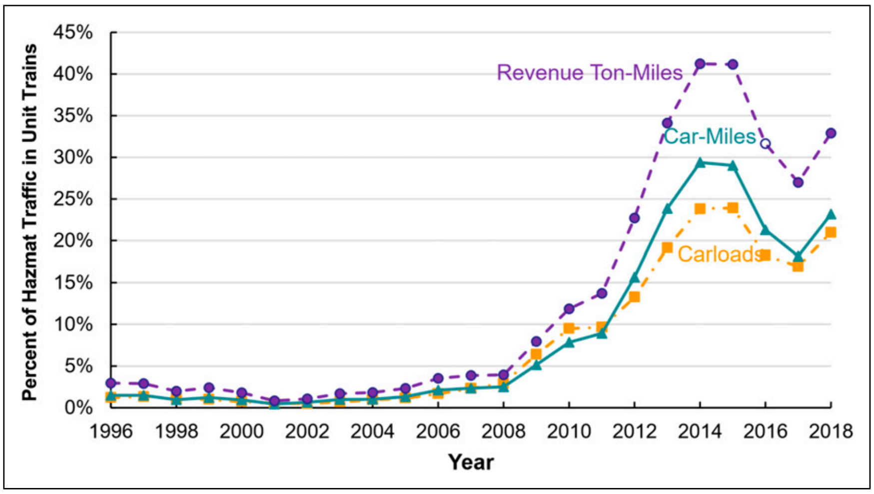

Figure 1. Fraction of hazmat traffic in unit trains (Dick et al., 2021).

transporting an increasing proportion of hazmat during the past two decades (Figure 1). Specifically, in 2018, approximately 21% of hazmat carloads moved in unit trains, generating 23% of hazmat car-miles and 33% of hazmat revenue ton-miles. This hazmat share of unit train traffic has increased substantially since 2008 when it comprised less than 1% of unit train traffic.

Despite significant growth of unit train transportation of hazmat commodities, to the authors' knowledge, there has been relatively little research focusing on the safety risk analysis of hazmat unit trains. Derailment is a common accident type on American freight railroads (Li et al., 2018; Liu et al., 2017). A previous study analyzed the derailment characteristics of loaded and empty unit trains (Li et al., 2018), but it did not address train-type-specific derailment rate or accident cause distributions. The next section summarizes the existing research regarding train derailment analyses and rail hazmat transportation that are relevant to the comparison of unit train and manifest train derailment frequency and derailment rate.

Literature review

Rail transports over two million carloads of hazmat in the U.S. annually (Liu et al., 2018), and over 99.999% of hazmat traffic by rail reaches its destination without a release caused by an incident (AAR, 2018). Bagheri et al. (2014) stated that rail is the preferred option for transporting large amounts of hazmat over long distances.

Unit trains increase freight railroad transportation efficiency. The rapid increase in crude oil transportation by rail in North America in recent years has led to more hazmat being moved in dedicated unit trains of 80 to 160 railcars (Dick and Lynn, 2014). In addition to unit trains, manifest trains may consist of both hazmat cars and non-hazmat cars. Liu (2017a) compared hazmat transportation risk in unit trains with manifest trains and found that a unit train has a higher probability of a release incident after a train derailment occurs. Moving large amounts of hazmat in a single unit train may increase the risk of multiple-car releases compared to transporting them in multiple manifest trains where each train contains fewer hazmat cars because there is generally disproportionately large consequences in large-hazmat-release events (Liu et al., 2012). However, it has also been recognized that transporting hazmat in unit trains can reduce the number of accidents involving hazmat cars because fewer trains are operated to transport the same amount of hazmat (Liu, 2017a).

In terms of derailment frequency analysis, previous studies (Li et al., 2018; Liu et al., 2018) used mainline derailment data from the US Department of Transportation Federal Railroad Administration (FRA) Rail Equipment Accident (REA) database. The statistical analysis of derailment causes, and multiple affecting factors, has been widely studied in the literature (Barkan et al., 2003; Liu, 2017b; Lin et al., 2020). Liu et al. (2012) identified the top frequent accident causes of train derailment occurrence, along with accident prevention strategies. Broken rails or welds have been shown to be the leading derailment causes on freight railroads (Li et al., 2018; Liu et al., 2012, Mohammadi et al., 2019). Furthermore, derailment rate, which is defined as the number of derailments normalized by traffic exposure, is a critical statistic for derailment analysis. A previous study (Liu, 2015) found that there is an annual declination rate of 5.6% in Class I mainline freight train derailment rates from 2000 to 2014. Later, Liu et al. (2017) concluded that the freight train derailment rates on Class I railroad mainlines are affected by FRA track class (a higher track class has a higher allowable maximum speed, and thus more stringent track geometry tolerances and maintenance standards), annual traffic density, and method of operation (signaled vs non-signaled). Besides these factors, the impact of train weight on derailment rate has been studied in the literature (Nayak and Palmer, 1980).

Knowledge gap and research objective

Despite these prior research efforts, one open question remained—does a unit train have a different derailment rate (likelihood) than a manifest train? Train-type-specific derailment rate analysis is important to further understand various options for transporting the same amount of hazmat. For example, if we have 100 tank cars of petroleum crude oil to transport, we may ship all of them in a single unit train, or alternatively, we can split them into multiple manifest trains. Which option will have a lower risk level on a given route? To address this question, in this paper the authors will:

- Develop a methodology to identify unit trains and manifest trains that improves upon and outperforms a previous method presented in Li et al. (2018);
- Estimate derailment rates for the unit train (particularly hazmat unit train) and manifest train; and
- Explore the impact of train length and weight on hazmat unit train and manifest derailment rate.

The research presented in this paper aims to provide the first analysis of train derailment rate and causes for unit trains and manifest trains. In particular, this paper will estimate the derailment rate and identify major derailment causes for hazmat unit trains, non-hazmat unit trains, and manifest trains. The new methodology and information developed from this research can support further efforts in developing train-type-specific risk analysis and management solutions for transporting hazmat in unit trains and manifest trains.

Methodology

Data sources

Derailment data in this study was derived from the FRA REA database, which records railroad accidents whose total infrastructure and rolling stock damage exceeds a monetary threshold (FRA, 2011). This reporting threshold is periodically adjusted to account for inflation, increasing from \$6300 in 1996 to \$11,200 in 2021 (FRA, 2012; FRA, 2021). Detailed accident information, including operational factors, environmental factors, train characteristics, damage conditions, and other information useful for understanding the circumstances and causes of accidents, are provided in the database (Li et al., 2018). The accident data used for the analysis in this research includes freight train derailments on Class I mainline railroads over the period from 1996 to 2018.

The traffic data analyzed in this study came from the Class I Railroad Annual Reports (Form R-1) from the STB (2020a), and STB Public Waybill Sample data (STB, 2020b). Since 1996, every US Class 1 railroad has been required to file an annual report with the STB (STB, 2020a). These annual reports, commonly referred to as the "R-1" Annual Report Financial Data, summarize various financial, asset ownership and operating data and statistics for each calendar year. Train-miles, car-miles, and gross ton-miles are three common metrics for measuring freight traffic and were used in this analysis. One train-mile is equivalent of running one train across one mile; one car-mile is equivalent of moving one railcar across one mile, and one gross ton-mile refers to transporting one ton of railcar and freight payload across one mile. If a train consisting of 100 rail cars and carrying 10,000 gross tons (including the weight of lading, railcar, and locomotives) moves one mile, it produces one train-mile, 100 car-miles, and 10,000 gross ton-miles. Train-miles, car-miles, and gross ton-miles data of unit trains and manifest trains were collected for each Class 1 railroad for the period 1996–2018. These statistics covered all railroad traffic during a given year, including hazmat and non-hazmat traffic.

Train type identification

This paper proposed a novel method to identify unit trains and manifest trains using railroad code, train symbol identification, causing car reporting mark and number, number of empty cars, number of loaded cars, number of locomotives, and narratives that were recorded in the REA database. The analytical process was described below.

First, several variables were extracted from the FRA REA database, including the number of locomotives, the number of empty cars, the number of loaded cars, the length of the train considering the total number of cars and locomotives, and the percentage of loaded or empty railcars in the train. In this research, a train was classified as loaded if 95% or more of its cars were loaded, or empty if 95% or more of its cars were empty (Figure 2). These percentages

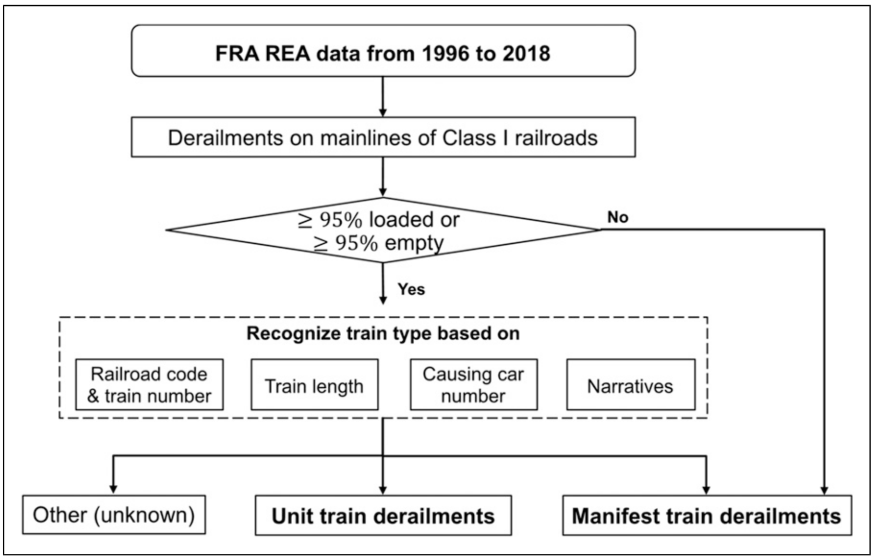

Figure 2. Methodology for classifying type of derailed trains.

were calculated by dividing the number of loaded or empty cars by the total number of cars in the train.

The percentage of "95%" of loaded cars or empty cars rather than the percentage of "100%" was used as the threshold to measure whether a train is a unit train or a manifest train because trains transporting hazmat generally have "buffer" cars (between the locomotives and the first hazmat car), as required by federal regulation (FRA, 2005). This threshold was also employed to identify the loading conditions (e.g., loaded trains, empty trains) of freight trains in the previous study (Li et al., 2018).

Next, to determine if a train was a unit train or a manifest train, we needed to identify train type when a train is more than 95% loaded or empty, while the remaining trains with partially loaded consist are deemed manifest trains. Four criteria were conducted as follows.

(1) The railroad code and train number fields in the FRA REA database were used to identify whether or not a derailment involved a unit train by utilizing individual railroads' train symbol systems (Train Symbols, 2020; Qstation, 2020). For example, based on BNSF Railway's symbol guide (Qstation, 2020), train numbers with prefixes of "C", "G", "U" represent loaded unit coal trains, loaded unit grain trains, and unit trains other than coal or grain, respectively, while "M" signifies manifest trains.
(2) As a train type for high-volume bulk commodities, the number of rail cars in unit trains are typically between 65 cars and 200 cars (or even more) in length (Aberdeen Carolina & Western Railway, 2020). This research classified all trains with smaller number of cars (e.g., fewer than 40 cars as the predetermined threshold) in length as manifest trains. For trains of over 40 cars, other key variables, such as causing car number and railroad code, were used to further identify unit trains.
(3) The equipment identification for the first car involved in the derailment was provided in the FRA REA database, and this information was used to assist the identification of train type.
(4) The FRA REA database also recorded narratives for reported train accidents. The narratives sometimes provide additional information, such as the incident train number, train and railcar types, and other keywords that can help distinguish between unit trains and manifest trains. For example, derailment records with narratives mentioning the terms "boxcar", "trailer", "container", or "local train" are likely to be manifest train derailments.

Note that this research focused on the mainline derailments of six Class I railroads in the US, while derailments of Kansas City Southern Railway (KCS) were not included in this research due to data limitation and some inconsistencies in historical traffic data records that would be introduced in the next section. From 1996 to 2018, in total, 2462 derailed trains were classified as unit trains, 5514 were classified as manifest trains, and 12 were classified as "other" trains of unknown type, which were excluded from further analysis.

Train type-specific derailment analysis

Train derailment statistics. Derailment statistics of unit trains and manifest trains were summarized and presented in this section. The train length was defined as the number of all types of railcars in consist, including loaded cars, empty cars, and locomotives. The residual train length was defined as the number of railcars after the position of the first derailed vehicle (FDV), while the normalized residual train length is the residual train length divided by the total train length.

As shown in Table 1, the average derailment speeds of manifest trains and unit trains had minor difference (24.3 mph and 25.1 mph, respectively), nor did the average normalized residual train lengths (57% and 54%, respectively). The significances of these two variables' differences between manifest trains and unit trains were also validated with a Pearson's chi-squared test. Pearson's chi-squared test is one of the most commonly used statistics that intend to evaluate the genetic association or difference between the sets (Agresti and Kateri, 2011; Zhang and Liu, 2020). The test showed that the p-values of two variables were greater than 0.05. Thus, the derailment speeds and residual train lengths of manifest trains and unit trains did not have significant difference in this study. The average weight of

Table 1. Derailment statistics by train type.

Group Average Tons per Average	Derailment frequency	Train length	Car (excl. locomotive)	Speed (mph)	Number of cars	Normalized by total train Length	Number of cars Derailed
					Average Residual Train Length		
Manifest trains	5.514	82.6	80.7	24.3	47	57%	7.6
Empty manifest	240	69.1	38.3	21.4	41	59%	6.8
Partially loaded manifest	3.925	88.9	78.3	24.3	49	55%	7.5
Loaded manifest	1.349	66.5	98.3	24.7	41	62%	7.9
Unit Trains	2.462	110	113.8	25.1	59	54%	11.3
Empty unit	421	110.6	29.1	24.9	70	63%	9.1
Loaded unit	2041	109.6	131.7	25.1	57	52%	11.7
Hazmat loaded unit	62	92.9	121.9	23.0	55	60%	11.5
Non-hazmat loaded unit	1.979	110.1	131.9	25.2	57	52%	11.8

unit trains (12,518 tons) was nearly twice that of manifest trains (6666 tons). In terms of the length of trains involved in derailments, manifest trains averaged 83 cars in consist and 81 tons per railcar, while unit trains averaged 110 cars in consist (around 33% more than manifest trains) and 114 tons per railcar (around 41% more). For derailment severity, manifest trains average 7.6 cars derailed per derailment, while unit trains derailed an average of 11.3 cars. Liu et al. (2013) indicated that derailment severity depended on derailment speed, residual length, and loading factor. Although derailment speed did not differ significantly, a higher value of residual train length and greater train weight resulted in more cars derailed in a unit train derailment compared to a manifest train derailment. The results were consistent with the positive correlations between derailment severity, train length, and loading status identified in previous research and the associated hypothesis that greater train length and weight of unit trains indicated greater kinetic energy in the derailment compared to manifest trains, thereby causing more cars to derail, given all else being equal (Liu et al., 2013).

Loaded unit trains transporting hazmat or non-hazmat bore similar characteristics in train length, train weight, residual train length, and derailment severity. The majority of loaded unit train derailments were non-hazmat loaded unit trains (e.g., coal trains), while only 62 of 2041 (3%) derailed unit trains carried hazmat.

Causal analysis

The FRA REA database has a code system for accident causes, and codes of similar causes are grouped. A variation on the FRA cause groups was developed in the early 1990s by Arthur D. Little (ADL) Inc. working with the Association of American Railroads (AAR) based on input from railroad engineering and mechanical experts (ADL, 1996). The objective of the ADL grouping was to better link accident causes that could be addressed through similar or related preventative measures. For example, broken rails, joint bars, and rail anchors that were combined in the same FRA subgroup were distinguished between broken rails or welds and joint bar defects in the ADL grouping (Zhang et al., 2021). In some cases, ADL also combined similar cause subgroups into one group (Li et al., 2018). As a result, the ADL grouping has been used in a number of causal analysis (Liu et al., 2012; Lin et al. 2020).

The first step in the causal analysis was to identify the top 10 frequent ADL cause groups for both train types and rank them by the number of derailments (Table 2). Broken rails or welds (08T) was the leading cause group for both train types. Broken rails accounted for about 12% and 18% of manifest train derailments and unit train derailments, respectively. Each broken-rail-caused manifest train derailment had an average of 12 cars derailed, while a broken rail-caused unit train derailment had average of 16 cars derailed. All of the top frequent cause groups for unit train derailments were car-mile-related causes (related to train length), except for the obstruction (01M). Obstruction (01M) included snow or ice on track, extreme weather conditions, or an object or equipment on or fouling track. For manifest trains, although over 50% of derailments resulted from car-mile-related accident causes, some train-mile-related causes (independent of train length) also contributed to a decent proportion of derailments, such as train handling (09H). Train handling (09H)

Table 2. Distribution of cause groups by train type. (a) Unit train derailments.

Rank	—	ADL cause group	ADL cause group	percentage (%)	Average number of cars derailed
1	08T	Broken rails or welds broken wheels (Car)	440	17.9	15.8
2	12E	Wheels (Car)	230	9.3	9.2
3	10E	Bearing failure (car)	182	7.4	7.5
4	05T	Buckled track	152	6.2	14.7
5	11E	Other axle/Journal defects (car)	152	6.2	8.3
6	04T	Track geometry (excl. Wide gauge)	141	5.7	7.8
7	01M	Obstructions	98	4.0	18.5
8	03T	Wide gauge	87	3.5	11.7
9	01T	Roadbed defects	71	2.9	12.9
10	13E	Other wheel defects (car)	70	2.8	6.0

(b)Manifest Train Derailments

Rank	—	ADL cause group	Number of darailments	percentage (%)	Average number of cars derailed
1	08T	Broken rails or welds	639	11.6	12.0
2	04T	Track geometry (excl. Wide gauge)	391	7.1	6.0
3	10E	Bearing failure (car)	343	6.2	5.2
4	09H	Train handling (excl. Brakes)	324	5.9	7.9
5	01M	Obstructions	243	4.4	10.8
6	04M	Track-train interaction	212	3.8	6.9
7	03M	Lading problems	211	3.8	5.5
8	03T	Wide gauge	186	3.4	9.0
9	07E	Coupler defects (car)	184	3.3	4.6
10	11H	Use of switches	182	3.3	4.0

Notes: Two tables present the statistics of top 10 causes only and other causes are not included.

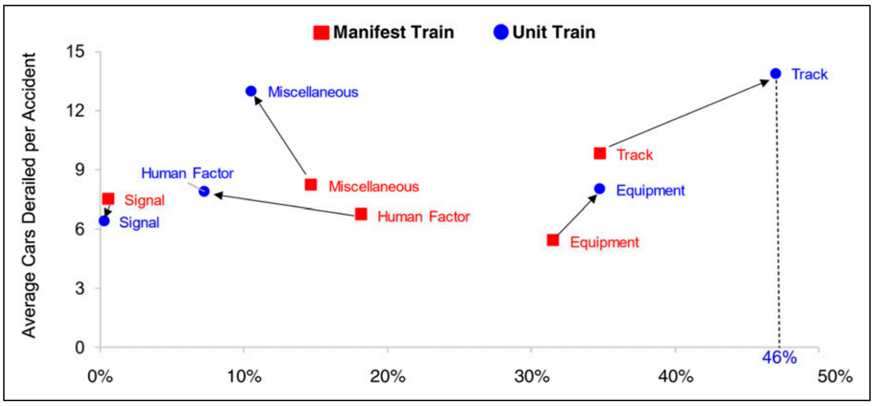

Figure 3. Distribution of cause groups in unit train and manifest train derailments.

included accidents caused by improper train make-up at initial terminal, improper placement of cars in train, excessive buff or slack action in train handling, and excessive lateral drawbar force on curve in train handling. A detailed discussion of train-mile-related and car-mile-related accident causes can be found in Wang (2019).

It was further found that a greater majority of unit train derailments resulted from track related and equipment-related causes, which are both car-mile related causes as classified by previous studies (ADL, 1996; Wang, 2019) (Figure 2). Unit trains involving heavier and more cars in consist on average resulted in greater track-related and equipment-related accidents than manifest trains. This may be related to the features of unit train weight and length that are able to cause more damage to track and rolling stock (due to dynamic loading). Besides, in terms of derailment severity, unit trains derailed more cars than manifest trains. The potential reason might still be the difference of train characteristics (e.g., train length, train weight) between these two train types. Meanwhile, manifest train derailments involved a relatively higher proportion of human factor-related causes and miscellaneous causes, which were mostly train-mile related causes. Figure 3 focused on the cause group distribution of derailment frequency and excluded the potential impact of traffic exposures in unit trains and manifest trains.

Derailment Rate Analysis by Train Type

Derailment rate comparison

Derailment rate is a useful statistic to estimate the likelihood of a derailment (Schafer and Barkan, 2008; Zhang et al., 2019). Three types of derailment rate metrics were covered in this study: derailment rate per million train-miles, rate per billion ton-miles, and rate per billion car-miles (Anderson and Barkan, 2004; Evans, 2011). Equations (1)–(3) showed the calculation of these rates with derailment frequency and traffic volumes

$$\text{Derailment rate per million train miles} = \frac{\text{Number of train derailments}}{\text{million train miles}} \quad (1)$$

$$\text{Derailment rate per billion ton miles} = \frac{\text{Number of train derailments}}{\text{Billion ton miles}} \quad (2)$$

$$\text{Derailment rate per billion car miles} = \frac{\text{Number of train derailments}}{\text{Billion car miles}} \quad (3)$$

Figure 4 presented the three derailment rates by overall breakdown of train type, loading conditions within unit trains, and whether or not hazmat was carried within loaded unit train. The following observations were made:

A unit train had 27% higher average train-mile based derailment rate than manifest trains, but it had approximately 40% lower average car-mile and ton-mile-based derailment rates. This is probably due to its greater length and weight. Unit trains transport large amount of goods in more cars compared to manifest trains, and therefore for a single train operation, unit trains are more prone to train-mile based derailments than a manifest train. On the other hand, since more cars and goods are put on the same train for unit train operation compared to manifest trains, for individual cars or units of goods, they experience less risk of train-mile based derailment compared to those cars or goods being put on manifest trains, while the chance for car-mile based derailments remain the same. Therefore, unit trains have lower car-mile or ton-mile-based derailment rates.

Within the category of unit trains, if the derailment rate was measured by million train-miles or billion car-miles, a loaded unit train had a four-time higher derailment rate than an empty unit train. If the derailment rate was measured by billion ton-miles, loaded unit trains still had higher rate than empty unit trains but by a smaller margin. It is reasonable for loaded unit train to have higher derailment rate than empty unit train because loaded trains impose greater load to rolling stock and track infrastructure and therefore increase the likelihood of failure (Sadeghi and Shoja, 2016). In addition, operating heavier trains require more power and braking control which increase the risk of derailments due to improper use or insufficient braking or power (McClanachan and Cole, 2012).

- Within loaded unit trains, hazmat loaded unit trains and non-hazmat loaded unit trains had close derailment

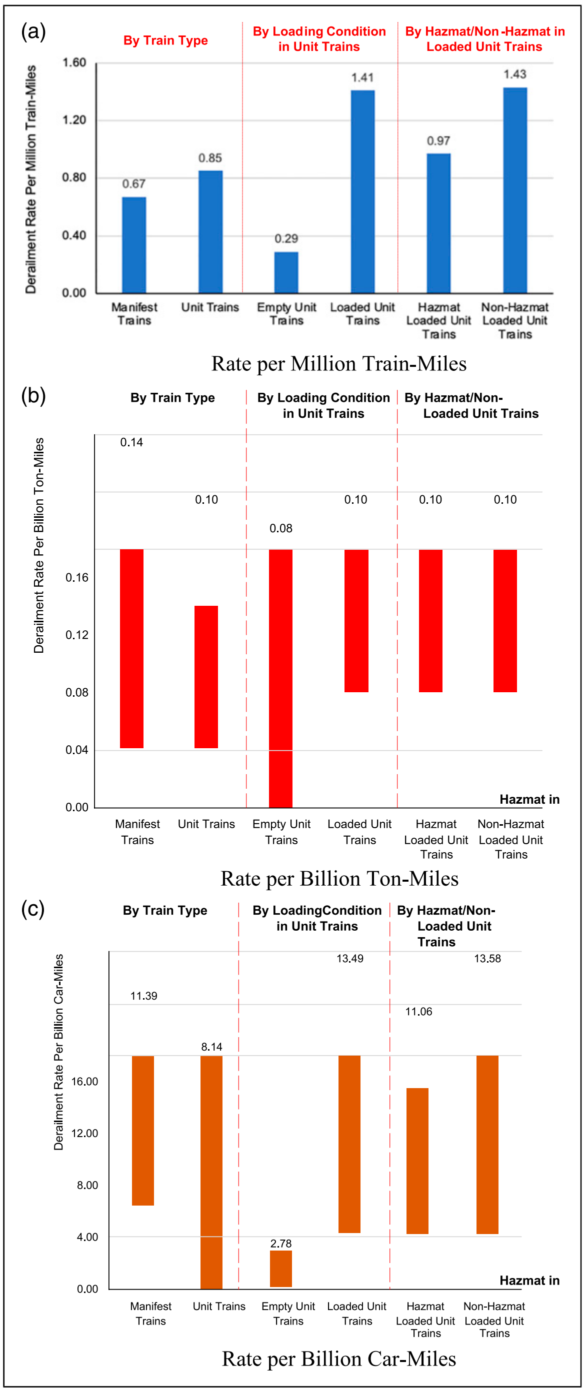

Figure 4. Derailment rate comparison by train type. (a) Rate per million train-miles, (b) rate per billion ton-miles, (c) rate per billion car-miles.

rates by ton-mile measure. With different traffic metrics, a hazmat loaded unit train had 0.97 derailments per million train-miles and 11.06 derailments per billion car-miles, which were approximately 40% and 20% lower than loaded non-hazmat unit trains, respectively. One possible reason for loaded hazmat unit train to have lower derailment rates than loaded non-hazmat train is the additional operational regulations and practices implemented on those trains as part of the hazmat release risk mitigation and reduction strategies (PHMSA, 2015).

- In comparison to manifest trains, hazmat loaded unit trains had lower derailments per billion ton-miles and per billion car-miles, although their derailment rate per million train-miles was slightly higher.

The Kolmogorov–Smirnov (KS) test was applied to determine the difference of derailment rates between unit trains and manifest trains within the study period. The KS test is a practical nonparametric, distribution-free test with no restrictions on sample size (Meng and Qu, 2012). Based on the p-values of derailment rate, the rates per billion ton-miles and billion car-miles of unit trains and manifest trains were statistically significantly different (p-values $< .001$) and the rates per million train-miles were slightly statistically different (p-value $= .04$). From Table 1, note that a loaded unit train had the longest average train length (110 cars per train) and the highest average tonnage per car (131.7) among the studied train groups. For the comparison of hazmat loaded unit trains and non-hazmat loaded unit trains, the length and the weight of non-hazmat loaded unit trains were 20% and 9% greater than those of hazmat loaded unit trains, respectively, for the derailments in the FRA database. Based on these statistics, the impact of train weight and train length on derailment rates were investigated in the next section.

Effect of train weight on loaded unit train derailment rate

As shown in Figure 4(b), empty unit trains and loaded unit trains had close derailment rates per billion ton-miles. However, the derailment rates per billion car-miles and derailment rates per billion car-miles of loaded unit trains were considerably higher than empty unit trains, differing by more than a factor of four. This was consistent with the conclusion of previous studies that accident rates per billion car-miles increased when using higher capacity cars (Nayak and Palmer, 1980; Wang, 2019).

A causal analysis was conducted to understand the potential impact of train weight on train derailment rate. As shown in Figure 5, the significant difference in derailment rates per million train-miles and derailment rates per billion car-miles between loaded unit trains and empty unit trains seemed to arise from track-related causes and equipment-related causes. Relatively minor dissimilarities existed in human factor-causes, miscellaneous causes, and signal causes, which were mostly train-mile-related causes. Given that one major difference between loaded unit trains and empty unit trains is train weight, the relationship between train weight and derailment rate may exist. It is presumed that heavier trains may cause more damage to track and rolling stock (due to dynamic loading), and thus may result in greater track-related and equipment-related accident likelihoods, given all else being equal.

Effect of train length on loaded unit train derailment rate

The distributions of derailment rates under varying loaded unit train lengths were presented in Table 3. In terms of derailment rate per million train-miles, four train-length categories (61–80 cars, 81–100 cars, 101–120 cars, and over 120 cars) had close rates. However, with greater train

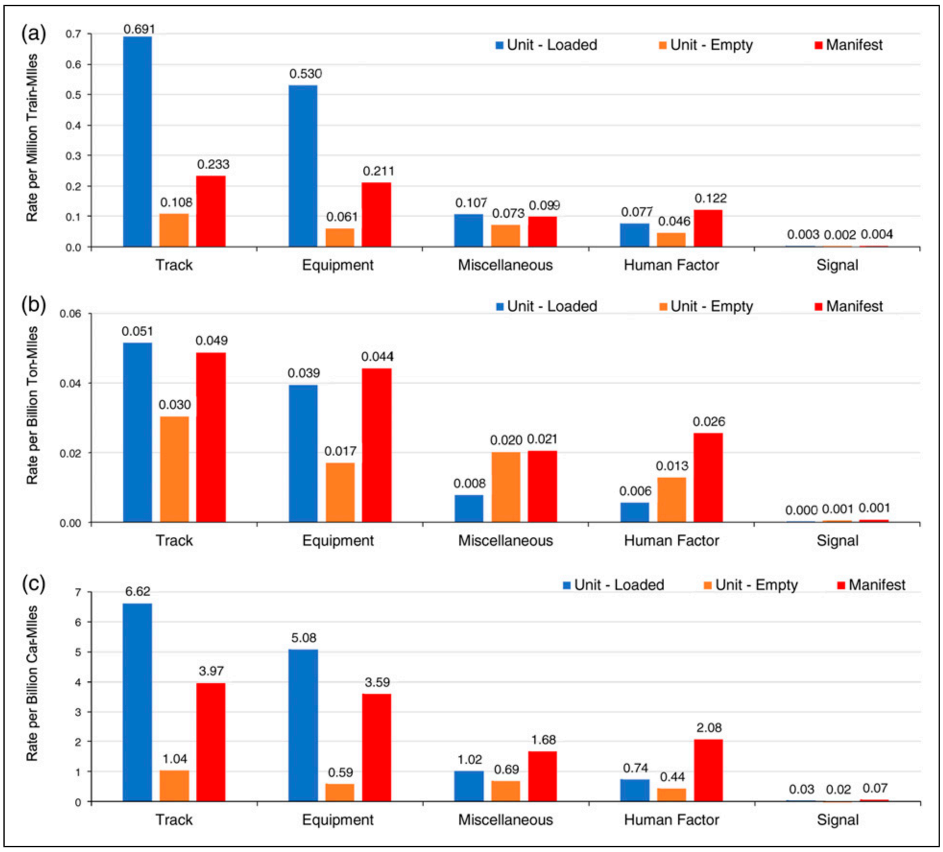

Figure 5. Derailment rates of loaded unit trains, empty unit trains, and manifest Trains(a) rate per million train-miles, (b) rate per billion ton-miles, (c) rate per billion car-miles.

Table 3. Loaded unit train derailment rates by train length.

Loaded unit trains	Rate per million Train-miles	Rate per billion Ton-miles	Rate per billion Car-miles
61–80 cars	1.57	0.22	21.54
81–100 cars	1.89	0.19	20.07
101–120 cars	1.47	0.12	13.10
121+ cars	1.29	0.08	9.80

length (particularly over 100 cars per train), derailment rates per billion car-miles and per billion ton-miles changed more significantly. For example, in terms of derailment rate per billion car-miles or per billion ton-miles, a loaded unit train with over 121 cars had only one-third of the rate for a loaded unit train shorter than 80 cars.

Figure 6 presented the derailment rates of different loaded unit train lengths under five causal groups (e.g., track, equipment, human factor, signal, and miscellaneous). The analysis showed that track-related and equipment-related causes accounted for the majority of loaded unit train derailments for all length categories. Furthermore, the derailment rates per billion ton-miles and rates per billion car-miles had decreasing trends with longer train lengths.

The decreasing trend in derailment rate per billion ton-miles and billion car-miles with increasing train length in Table 3 and Figure 6 is intuitive as the longer train lengths exhibit economies of scale. Longer trains require fewer train movements to transport the same number of ton-miles and car-miles. Since the occurrence of train-mile related causes (such as those in the human factors and miscellaneous groups) are spread over a larger number of ton-miles and car-miles per train movement, the overall rate is expected to decrease with increasing train length.

The trend in train-miles rates as a function of train length in Table 3 and Figure 6 is less clear. The expectation would be that as loaded unit trains become longer and heavier, each train would impart more damage to the track infrastructure and pose a greater train handling challenge, and the rate per train-mile should increase with train length. However, this trend is not observed. It is possible that the derailment rates among these four train length groups (e.g. 61–80 cars, 81–100 cars, 101–120 cars, and over 120 cars) have a confounding relationship with other factors. One example is FRA track class. Trains of longer length may be more prevalent on certain routes with higher track class because higher track classes indicate better track maintenance standards (Liu et al., 2017) and therefore can bear more traffic loads in general. Further support for this hypothesis was provided by the loaded train derailment rates per ton-mile and car-mile for the track and equipment cause groups in Figures 6(b) and (c). Since these causes were related to car-miles (and by extension ton-miles), they should show similar rates across all train lengths, but instead they were observed to decline with increasing train length. However, this behavior could also be explained if a disproportionate number of long trains are operating on higher quality track where each car-mile and ton-mile has a lower likelihood of derailment. To address this possibility,

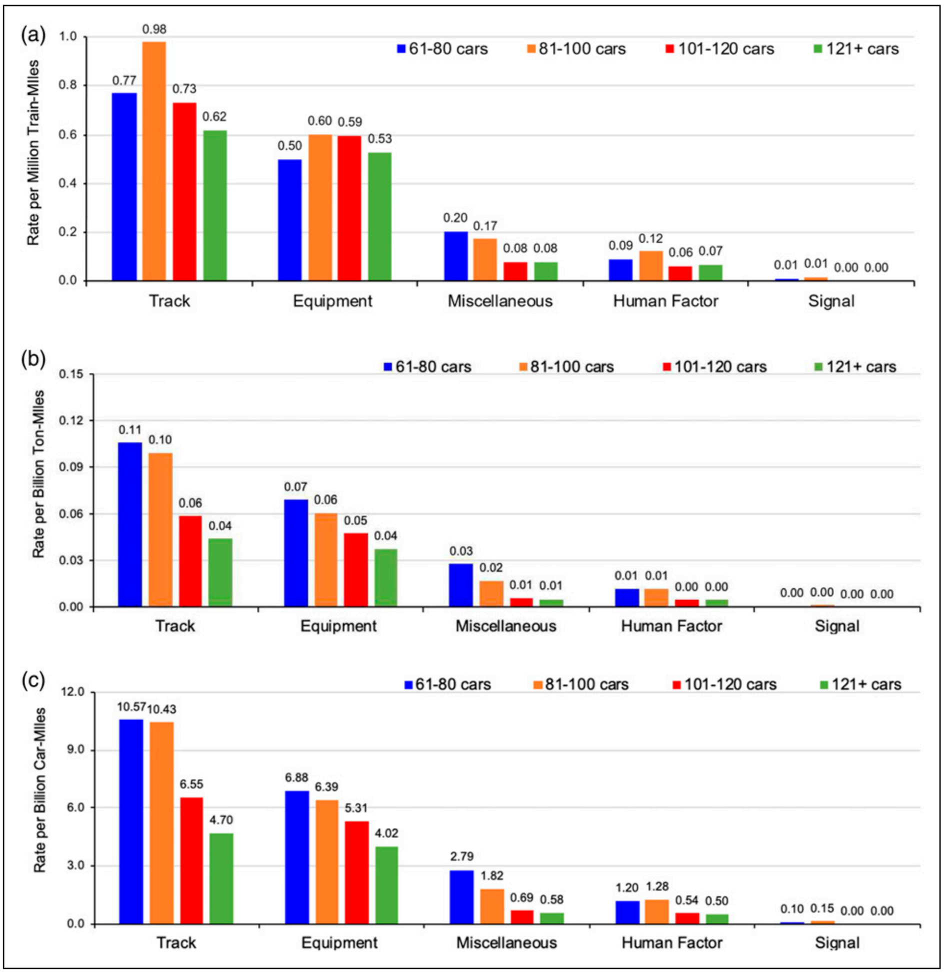

Figure 6. Derailment rates of loaded unit trains under different train lengths. (a) Rate per million train-miles, (b) rate per billion ton-miles, (c) rate per billion car-miles.

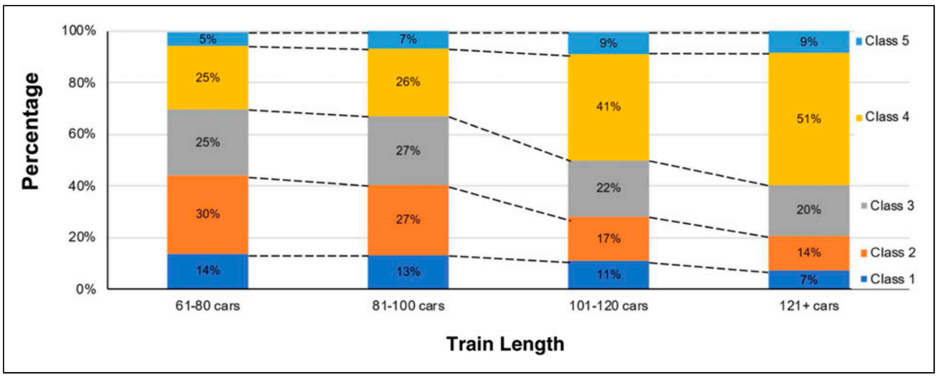

Figure 7. Loaded unit train derailments by train length and FRA track class.

we further investigated the relationship between train length and FRA track class for FRA-reportable derailments on mainlines.

Figure 7 showed that over half of loaded unit train derailments with shorter train lengths (e.g., fewer than 100 cars) occurred on FRA track Class 1, Class 2, and Class 3. In comparison, longer trains (e.g., greater than 100 cars) had a greater proportion of derailments on FRA track Class 4 and Class 5, probably because these longer unit trains were operated on high-tonnage corridors whose tracks were maintained at high track classes. This comparison was based on derailment frequency and did not account for traffic volumes by track class (in fact, the majority of traffic volume in Class I railroads was on track Class 3 or higher). Because track-class-specific traffic data was not available to the authors during the writing of this manuscript, derailment rate calculation by track class and train length in combination was not developed but may be considered in the future if data become available.

Conclusions

This study analyzed freight train derailment rates for manifest trains and unit trains. The effect of loading condition, whether trains are carrying hazmat, train length, and train weight on derailments rates of these two types of trains were analyzed and compared. Causal analyses were conducted to assist in interpreting the similarities and differences in these accident characteristics. In terms of derailment rate per million train-miles or per billion car-miles, a loaded unit train had a four-fold higher rate than an empty unit train. Within loaded unit trains, a loaded hazmat unit train had a 30% lower rate per million train-miles, a 20% lower rate per billion car-miles, compared to a loaded non-hazmat unit train. Besides, in comparison to manifest trains, hazmat loaded unit trains had a 28% lower derailment rate per billion ton-miles and slightly lower rate per billion car-miles. The research presented in this paper contributed to the development of a comprehensive and quantitative risk assessment of hazmat unit train and manifest train transportation. There has been strong interest in the rail industry to understand the comparison of safety and efficiency of transporting hazmat in unit trains and manifest trains under various operating circumstances. Questions can be asked such as "What are the risks of transporting the same amount of hazmat in unit trains and manifest trains, considering derailment rates on mainline and in the yards, conditional probability of releases, and consequences?" or "What is the tradeoff of transporting hazmat in unit trains and manifest trains in terms of operation efficiency (e.g., number of times hazmat cars need to be transferred in yards) while maintaining at least the same level of safety?" Ultimately, the objectives of improving hazmat transportation efficiency and safety will turn into an optimization problem, and the results presented in this paper formed a solid foundation and provided important information to achieve this goal and addressed one of the timely and critical railroad transportation questions.

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ORCID iDs

Chen-Yu Lin https://orcid.org/0000-0003-0337-5230
Xiang Liu https://orcid.org/0000-0002-4348-7432
C Tyler Dick https://orcid.org/0000-0002-2527-1320

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