Analysis of Major Derailment Causes on Heavy Haul Railways in the United States

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Abstract

Train derailments may cause damages to railway infrastructure, rolling stock and the environment, service disruptions, casualties and other undesirable consequences. Therefore, improving train operating safety has long been a high priority of the railway industry and government. Train derailments occur due to a variety of different causes, and may vary in their frequency and severity depending on operating conditions. Consequently, efficient allocation of resources to prevent derailments in the most cost-efficient manner requires understanding which factors and under which circumstances account for the greatest risk. In this paper, freight-train derailment data from Federal Railroad Administration (FRA) of U.S. Department of Transportation (U.S. DOT) from 2001 to 2010 were analyzed to quantitatively evaluate the relationship between freight-train derailment frequency and severity and infrastructure and rolling stock characteristics by major derailment cause. This study develops an analytical framework for conducting accident-cause-specific derailment analysis and it is intended to aid the rail industry and government in developing, evaluating, prioritizing and implementing measures to efficiently improve transportation safety.

1. Introduction

Derailments are a common type of freight-train accidents in the United States. Derailments occur due to a variety of causes, but some causes are much more prevalent than others. Furthermore, derailment frequency and severity also vary widely, dependent on the particular accident cause [1-4]. Efficient allocation of resources to prevent derailments on heavy haul railways requires understanding which factors and under which circumstances account for the greatest risk. Assessment of the benefits and costs to mitigate each accident cause can then be evaluated so that the greatest safety improvement can be achieved at any level of available resources.

The objective of this study is to develop statistical models to analyze the distribution of derailment frequency and severity by major accident cause. A logistic regression model is developed to estimate the probability that a freight-train derailment is due to a specific accident cause under various operating conditions. Derailment severity, defined as number of cars derailed in this study, is estimated using a zero-truncated negative binomial regression model. This paper focuses on Class I freight railways in the U.S. (operating revenue exceeding $378.8 million in 2009), which accounted for approximately 68% of route miles, 97% of total ton-miles and 94% of the total freight rail revenue [5]. Although serious incidents can and do occur on yard and siding tracks, the focus of this research is on mainline derailments because of the higher speeds and longer consists typical of mainline operation. The greater mass and speed means that the force and potential impact in terms of property damage, casualties and environmental impacts are all correspondingly greater [4].

2. Train Accident Causes

The Federal Railroad Administration (FRA) of U.S. Department of Transportation (U.S. DOT) specifies 389 distinctive accident cause codes in the Rail Equipment Accident (REA) database. These cause codes are hierarchically organized and categorized into major cause groups - track, equipment, human factors, signal and miscellaneous [6]. In a previous study, Arthur D. Little Inc.

(ADL) combined similar cause codes into the same group based on expert opinion [7]. ADL's grouping is similar to FRA's subcause group but allows for greater resolution of certain causes. For example, FRA combines broken rails, joint bars and rail anchor in the same subgroup, whereas ADL's grouping distinguishes between broken rail and joint bar defects. In this study, we use ADL's accident cause groups to analyze accident-cause-specific derailment frequency and severity. Derailment frequency and severity (average number of cars derailed) were plotted against one another, with frequency on the abscissa and severity on the ordinate (Fig. 1). The graph is divided into four quadrants on the basis of the average derailment frequency and severity along each axis. It enables an easy comparison of the relative frequency and severity of different accident causes.

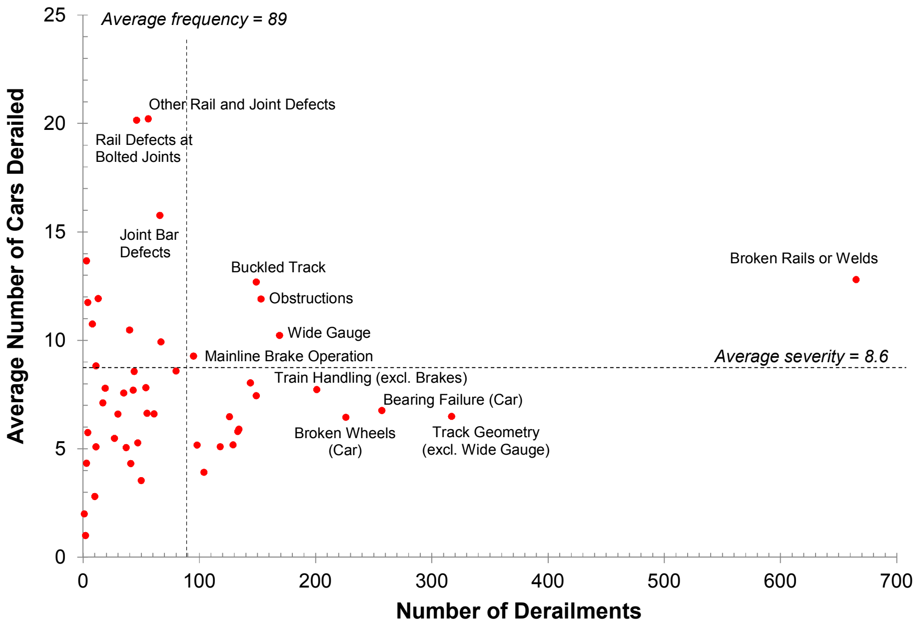


Fig. 1 Frequency and Severity Graph of Freight-Train Derailments, Class I Mainlines, 2001-2010 ([4])

Those in the upper right quadrant are most likely to pose the greatest risk because they are both more frequent and more severe than the average. These five cause groups are:

- Broken Rails or Welds
- Wide Gauge
- Buckled Track
- Obstructions
- Mainline Brake Operation

Four other cause groups that are notable due to their high frequency of occurrence are:

- Track Geometry (excluding Wide Gauge)
- Bearing Failure (Car)
- Broken Wheels (Car)
- Train Handling (excluding Brakes)

Three other cause groups are notable because of the high average severity of the resultant derailments, and because they are all due to related causes:

- Rail Defects at Bolted Joints
- Other Rail and Joint Defects
- Joint Bar Defects

Broken rails or welds were the most common accident causes from 2001 to 2010, accounting for about 15% of all derailments and correspondingly 23% of derailed cars on Class I mainlines [4]. Understanding train derailment likelihood by accident cause given specific operating conditions could help evaluate the safety effectiveness of derailment prevention strategies.

3. Derailment Frequency by Cause

We consider derailment frequency distribution by accident cause under different operating conditions, characterized by FRA track class, annual traffic density and method of operation. We consider two categories of FRA track class: lower track classes (classes 1 to 3) and higher track classes (classes 4 to 5). FRA Track Safety Standards require more frequent rail inspections on track classes 4 and 5 than the other lower track classes [8]. We classify method of operation by a non-signaled track versus a signaled track. We consider two levels of annual traffic density (million gross tons or MGT) with a division at 20MGT, which represents the average track traffic density on U.S. Class I railroads [9].

Table 1 and Fig. 2 present the distribution of FRA-reportable freight-train derailments on Class I mainlines due to broken rails and bearing failures, respectively, from 2001 to 2010. It suggests that non-signaled track territories may have a greater proportion of broken-rail-caused derailments than signaled tracks. In addition, higher track classes may have a higher likelihood of a bearing-failure-caused derailment.

Table 1 Derailment Frequency by Accident Cause, Class I Mainlines, 2001 to 2010

			Number of Train Derailments		Percentage of All Causes	
Track Class	Annual Traffic Density	Method of Operation	Broken Rails	Bearing Failures	Broken Rails	Bearing Failures
Class 1 to 3	<20MGT	Non-Signaled	167	22	26.7%	3.5%
Class 1 to 3	<20MGT	Signaled	42	14	10.1%	3.4%
Class 1 to 3	≥20MGT	Non-Signaled	35	10	22.9%	6.5%
Class 1 to 3	≥20MGT	Signaled	61	20	10.6%	3.5%
Class 4 to 5	<20MGT	Non-Signaled	35	13	19.7%	7.3%
Class 4 to 5	<20MGT	Signaled	31	26	10.7%	9.0%
Class 4 to 5	≥20MGT	Non-Signaled	34	21	21.4%	13.2%
Class 4 to 5	≥20MGT	Signaled	110	93	10.3%	8.7%

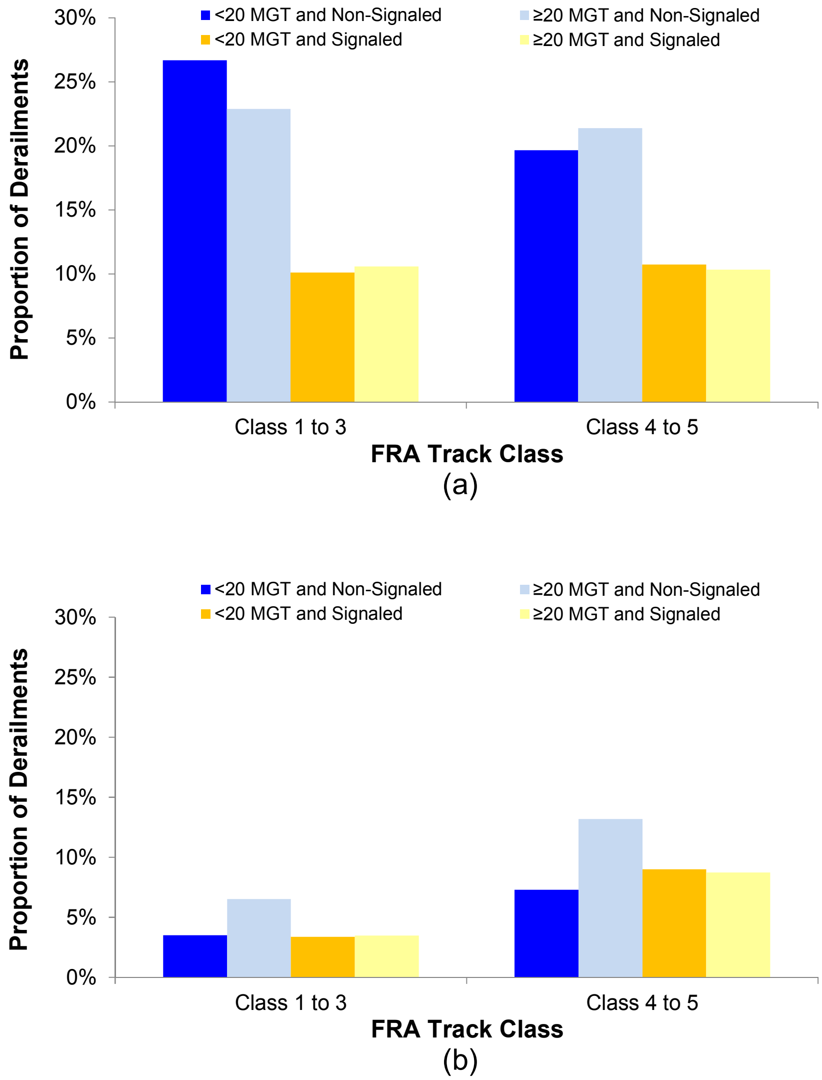


Fig. 2 Proportion of Freight-Train Derailments by Cause, Class I Mainlines, 2001-2010, (a) Broken Rails (b) Bearing Failures

A logistic regression model is developed to examine the hypothesis that the method of operation and FRA track class can affect the probability that a train derailment is due to broken rails or bearing failures, respectively. The likelihood-ratio (LR) test [10] is used to examine the effect of FRA track class, method of operation (non-signaled versus signaled) and annual traffic density level (<20MGT versus ≥20MGT) on the probability that a car derailment is due to broken rails. Table 2 shows that FRA track class and annual traffic density do not significantly affect the probability that a freight-train derailment is caused by broken rails, whereas method of operation is a significant factor. It shows that a non-signaled track territory has a greater proportion of derailments caused by broken rails than a signaled track. A similar model is developed for bearing-failure-caused derailments. It shows that higher track classes 4 and 5 have a greater proportion of bearing-failure-caused derailments than lower track classes 1 to 3.

TABLE 2 Likelihood Ratio Test of Effect of FRA Track Class, Method of Operation and Annual Traffic Density on the Probability that A Train Derailment is Due to (a) Broken Rails (b) Bearing Failures

(a) Broken Rails

Source	DF	Chi-Square	Pr > ChiSq
MOO	1	80.02	<.0001
Class	1	1.32	0.2501
Density	1	0.14	0.7055

(b) Bearing Failures

Source	DF	Chi-Square	Pr > ChiSq
MOO	1	2.02	0.1552
class	1	36.49	<.0001
Density	1	1.81	0.1784

Notes:
MOO = method of operation (1 represents signaled track, 0 otherwise)
Class = FRA track class (1 represents track classes 4 and 5, 0 otherwise)
Density = annual traffic density (1 represents annual traffic density ≥20MGT, 0 otherwise)

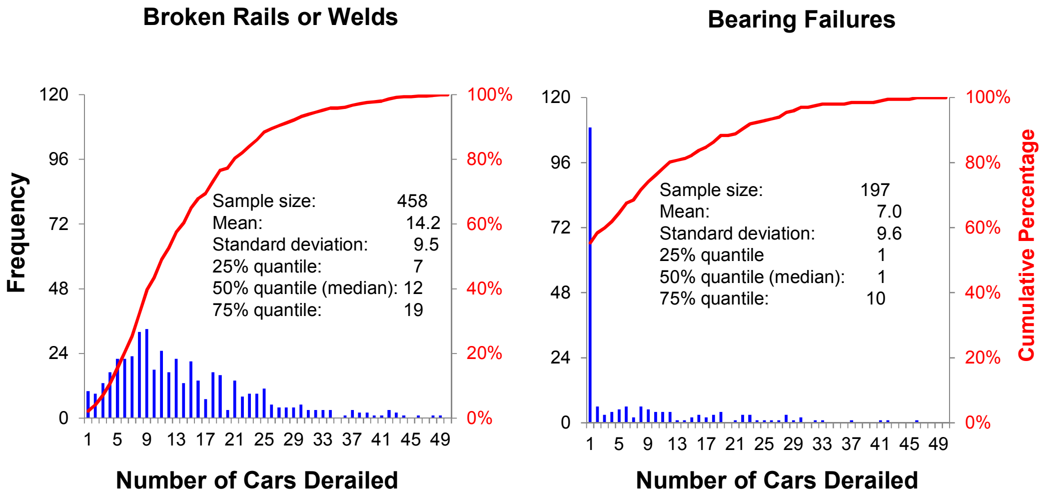
Table 3 presents the estimated proportion of freight-train derailments caused by broken rails and bearing failures, respectively. It shows that the relative frequency of accident causes could differ by operating conditions. For example, broken rails and bearing failures may result in equal number of train derailments in the high-track-class-high-traffic-density signaled track territory (10.4% versus 9.1%). However, in the low-track-class-low-traffic-density non-signaled track territory, the number of broken-rail-caused derailments is higher than bearing failures by a factor of 7 (24.3% versus 3.7%). Note that the regression analysis reveals the correlation between the response variable with covariates, it does not necessarily represent the cause-effect relationship. Also, the estimate probability should be interpreted in a relative other than absolute term. It means that the probability represents the likelihood that a derailment is due to a specific cause compared to other causes. It does not indicate the probability of a train derailment occurrence.

TABLE 3 Estimated Probability that A Train Derailment is Due to An Accident Cause

			Percentage of All Causes	
Track Class	Annual Traffic Density	Method of Operation	Broken Rails	Bearing Failures
Class 1 to 3	<20MGT	Non-Signaled	24.3%	3.7%
Class 1 to 3	<20MGT	Signaled	10.4%	3.7%
Class 1 to 3	≥20MGT	Non-Signaled	24.3%	3.7%
Class 1 to 3	≥20MGT	Signaled	10.4%	3.7%
Class 4 to 5	<20MGT	Non-Signaled	24.3%	9.1%
Class 4 to 5	<20MGT	Signaled	10.4%	9.1%
Class 4 to 5	≥20MGT	Non-Signaled	24.3%	9.1%
Class 4 to 5	≥20MGT	Signaled	10.4%	9.1%

4. Derailment Severity Modeling

Monetary damage is often used to assess the severity of train derailments. However, it is subject to many variables, such as the cost difference between locomotives and freight railcars, and the difference in repairing regular track versus special trackwork [1]. Instead, number of cars derailed may represent the physical forces in the train derailment. Broken rails and bearing failures are the leading track-related and equipment-related accident causes on Class I mainlines, respectively [1, 3, 4]. The distribution of derailment severity by these two accident causes are presented in Fig. 3. It shows that the two accident causes have different derailment severities. For example, 55% of bearing-failure-caused derailments had only one car derailed. By contrast, broken rails or welds are likely to cause more cars derailed, given all else being equal. Therefore, of interest is to understand the derailment severity function within each accident cause group.



(a) (b)

Fig. 3 Number of Cars Derailed in Freight-Train Derailments Due to (A) Broken Rails or Welds (B) Bearing Failures, Class I Mainlines, 2001-2010

The minimum number of cars derailed is 1. The traditional count data modeling techniques, such as Poisson or negative binomial regression is not applicable to the data excluding zeros [10]. In this paper, we develop a zero-truncated negative binomial regression (ZTNB) model to analyze train derailment severity data by accident cause. The methodologies of ZTNB were discussed in detail in Long [10]. Previous studies found that normalized point-of-derailment (NPOD), derailment speed (Speed), train length (Length) all affect train derailment severity [2, 11-14]. In this study, we study two new potential factors: percentage of loaded railcars in the train (Loading) and distribution of train power (Power). The null hypothesis is that a train carrying a larger proportion of loaded cars may derail more cars. This may in part be explained by the greater moment of inertia of loaded cars as opposed to empty cars, and correspondingly a longer braking distance. In addition, a larger proportion of loaded cars in the train may also indicate greater kinetic energy in the derailment, thereby causing more cars to derail. In addition, another new variable considered in this study is distribution of train power (Power). In this study, freight-trains are classified by two types: (1) trains with only head end locomotives and (2) trains with head end locomotives and additional locomotives in other positions (typically in the middle and/or in the rear). A binary variable (1 represents a distributed-power train, 0 represents the train with only head end locomotives) is created to examine the hypothesis that the two types of trains do not have statistically different derailment severity functions. A statistical software *Stata* is used to estimate the parameters in the ZTNB model. Table 4 presents the parameter estimates for broken rails and bearing failures, respectively. It shows that, *ceteris paribus*:

- Normalized point-of-derailment (NPOD) affects the derailment severity for both accident causes. The nearer the point-of-derailment is to the front, the more cars may derail.
- The effect of speed is significant for broken rails. The higher the speed, the more cars derailed. However, derailment speed does not significantly affect the derailment severity due to bearing failures. The insensitivity of derailment severity with respect to derailment speed for bearing- failure-caused derailments was also reported in [3].
- A longer train is more likely to derail more cars for both causes.
- A train with a higher percentage of loading cars may derail more cars for both causes.
- Distributed train power does not significantly reduce derailment severity for both causes given other factors.

Table 4 Zero-Truncated Negative Binomial Modeling of Derailment Severity

	Broken Rails			Bearing Failures		
Variable	Coefficient	Standard Error	P>|z|	Coefficient	Standard Error	P>|z|
Intercept	1.206	0.096	0.000	-23.004	122.822	0.856
NPOD	-0.877	0.073	0.000	-2.469	0.587	0.000
Speed	0.024	0.002	0.000	0.015	0.014	0.287
Length	0.009	0.001	0.000	0.019	0.006	0.002
Loading	0.256	0.068	0.000	1.500	0.607	0.014
Power	-0.076	0.064	0.235	-0.855	0.539	0.113

5. Discussion

This study has several implications to train accident analysis and prevention. The probability that a train derailment is due to a specific accident cause can be estimated using a logistic regression model. The analysis shows that different track conditions may have different effects on accident cause distribution. Therefore, the safety effectiveness of accident prevention activities may vary in different track territories. Train derailment severity data excludes zeros, thus requires an appropriate statistical model. We develop a zero-truncated negative binomial regression model to analyze the effects of several factors on freight-train derailment severity. The same factors may have different impacts on different accident causes.

Accident-cause-specific derailment frequency and severity should be appropriately considered in the accident prevention. This study provides a quantitative framework to assess the relative risk of major derailment causes on heavy haul railways, by quantifying the parametric relationship between derailment frequency and severity and operating characteristics. Ultimately, the statistical modeling of derailment frequency and severity by accident cause can be incorporate into a larger decision framework for optimizing the safety improvement under limited resources.

6. Conclusions

This study develops statistical models to analyze major train derailment causes on U.S. heavy haul railways. A logistic regression model is developed to estimate the relative derailment frequency by accident cause. It shows that accident-cause-specific derailment frequency may differ by track characteristics. A zero-truncated negative binomial model is developed to estimate the number of cars derailed by accident cause. The results could potentially provide the rail industry and government information to evaluate the effectiveness of accident prevention strategies for reducing derailment risk.

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