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Analysis of Causes of Major Train Derailment and Their Effect on Accident Rates

Xiang Liu, M. Rapik Saat, and Christopher P. L. Barkan

Analysis of the causes of train accidents is critical for rational allocation of resources to reduce accident occurrence in the most cost-effective manner possible. Train derailment data from the FRA rail equipment accident database for the interval 2001 to 2010 were analyzed for each track type, with accounting for frequency of occurrence by cause and number of cars derailed. Statistical analyses were conducted to examine the effects of accident cause, type of track, and derailment speed. The analysis showed that broken rails or welds were the leading derailment cause on main, yard, and siding tracks. By contrast to accident causes on main tracks, bearing failures and broken wheels were not among the top accident causes on yard or siding tracks. Instead, human factor–related causes such as improper use of switches and violation of switching rules were more prevalent. In all speed ranges, broken rails or welds were the leading cause of derailments; however, the relative frequency of the next most common accident types differed substantially for lower-versus higher-speed derailments. In general, at derailment speeds below 10 mph, certain track and human factor causes—such as improper train handling, braking operations, and improper use of switches—dominated. At derailment speeds above 25 mph, those causes were nearly absent and were replaced by equipment causes, such as bearing failure, broken wheel, and axle and journal defects. These results represent the first step in a systematic process of quantitative risk analysis of railroad freight train safety, with an ultimate objective of optimizing safety improvement and more cost-effective risk management.

Train accidents cause damage to infrastructure and rolling stock as well as service disruptions, and may cause casualties and harm the environment. Accordingly, improving train operating safety has long been a high priority of the rail industry and the government. Train accidents occur as a result of many different causes; however, some are much more prevalent than others. Furthermore, the frequency and severity of accidents also varies widely, depending on the particular accident cause (*1–3*). Efficient allocation of resources to prevent accidents in the most cost-effective manner possible requires understanding which factors account for the greatest risk, and under which circumstances. Assessment of the benefits and costs of strategies to mitigate each accident cause can then be evaluated and resources allocated so that the greatest safety improvement can be achieved for the level of investment available. This paper presents statistical results representing the first step in a systematic process of quantitative risk analysis and risk management for railroad freight train safety.

APPROACH

The approach taken in this research is to conduct detailed analysis of the train accident data supplied by the railroads to FRA of the U.S. Department of Transportation. FRA regularly publishes statistical summaries of these data; however, the results are generally presented at a highly aggregated level. Further insights are possible by analyzing the results in more detail and considering other statistical approaches. In addition, there are various metrics that can be used to assess train safety. The effectiveness of specific risk reduction strategies needs to be understood when the cost-effectiveness of research, development, and implementation of new strategies is considered. Consequently, in the final section of this paper a preliminary sensitivity analysis of several groups of accident causes is conducted to understand how changes in practice or failure prevention technology might affect the overall accident rate. The results enable objective comparison of different approaches that could be used to inform decision making by industry and government concerning which research, development, or implementation strategies to invest in.

DATA SOURCES AND ANALYSIS

FRA requires railroads to submit detailed reports of all significant accidents or incidents associated with railroad train operation. It is useful to review briefly the FRA databases in the larger context of railroad safety and analysis, including how the databases relate to one another and the hierarchical organization of the train accident database, which is the subject of the research described in this paper. These databases can be considered at increasing levels of detail as follows: type of incident (corresponding to particular FRA databases) and, within the database on train accidents, by track type, accident type, and accident cause.

FRA DATABASES

FRA maintains three major databases, each related to a different aspect of train operating safety: train accidents, employee casualties, and railroad and highway grade crossing incidents. A particular

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reportable event may require that reports be submitted to any or all of these, alone or in combination, depending on the circumstances. Of principal interest for the research described in this study is the first database describing the circumstances, physical characteristics, and other information related to damage to rolling stock and infrastructure. Within this database the interest lies in the type of track—main, siding, yard, or industry—that an accident occurred on. At the next level down, interest is focused on the type of accident, that is, derailment, collision, or various other types. Finally, within each of these track and accident types the particular cause of the accident and other circumstances, notably derailment speed, are the focus of interest.

Event Category and Corresponding FRA Database

The Rail Equipment Accident/Incident Report (REAIR) form (FRA F 6180.54) is used by railroads to report all accidents that exceed a monetary threshold of damages to infrastructure and rolling stock. [The form accounts for damage to on-track equipment, signals, track, track structures, and roadbed. The reporting threshold is periodically adjusted for inflation and increased from $7,700 in 2006 to $9,400 in 2011 (4).] FRA compiles these reports into the rail equipment accident (REA) database, which records rail equipment accident data dating back to 1975. In addition to the REAIR, the Highway–Rail Grade Crossing Accident/Incident Report (FRA F 6180.57) and Death, Injury, or Occupational Illness Summary (FRA F 6180.55a) are the other two principal eponymous railroad accident and incident reporting forms. A single accident may require more than one report, depending on its circumstances. For example, if a train accident occurs that results in damages to track and equipment exceeding the threshold, an FRA F 6180.54 report must be submitted, and if the accident involved a highway user at a highway–rail crossing, regardless of impact, a Form FRA F 6180.57 must also be completed. All casualties resulting from a reportable rail equipment accident, in addition to being recorded on Form FRA F 6180.54, must also be reported individually on Form FRA F 6180.55a (4). This study used data exclusively from the FRA REA database. Depending on the nature of one's interest in train accident analysis, additional useful information may be found in the other databases and these databases can be linked to pursue additional questions not possible with a particular database alone (5).

FRA Rail Equipment Accident Database

The FRA REA database records railroad, accident type, location, accident cause, severity, and other information important for accident analysis and prevention. This paper focuses on Class I freight railroads (operating revenue exceeding $378.8 million in 2009), which account for approximately 68% of U.S. railroad route miles, 97% of total ton-miles transported, and 94% of the total rail freight revenue (6). In addition to analysis of the number of freight trains derailed due to various causes, consideration of statistics on the number of cars derailed and the circumstances of their derailment is necessary because accident severity varies among different accident causes. To understand the effect of various derailment prevention strategies, first there is a need to quantify how much different accident causes contribute to derailment risk and also how accident characteristics affect the risk.

ACCIDENT BY TRACK TYPE

Four types of tracks are recorded in the FRA REA database—main, siding, yard, and industry tracks. These track types are used for different operational functions and consequently have different associated accident types, causes, and consequences. Train accidents are categorized into derailment, collision, highway–rail grade crossing accident, and several other less frequent types. When there is more than one type of accident, the type of accident that occurred first would be designated for all reports related to it. For example, a derailment caused by a collision would be classified as a "collision." Highway–rail grade crossing accidents in the REA database include only those that occur at the highway–rail interface and involve at least one highway user (4).

FRA-reportable freight train accident data for Class I railroads for the period 2001 to 2010 were compiled to show the number of FRA-reportable accidents, the average number of cars derailed per accident, and the total number of cars derailed by accident type and track type (Table 1). Train derailment was the most common type of accident on each track type, and train collision was the least frequent (excluding highway–rail grade crossing accidents on siding, yard, and industry tracks). Ninety-eight percent of highway–rail grade crossing accidents occurred on main track and accounted for 20% of all types of Class I main-line train accidents. By definition, these accidents exceeded the FRA reporting threshold for damages, but often did not result in a derailment (5). Accident severity is defined in this study as the number of cars derailed per accident and varies by track type and accident type. Train derailments on main and siding tracks had a greater average accident severity than did other types of accidents and tracks. Highway–rail grade crossing accidents had fewer cars derailed per accident because many reportable highway–rail grade crossing accidents resulted in no derailment (5).

Total number of cars derailed accounts for accident frequency and severity. The majority of cars derailed on Class I freight railroads were derailed as a result of train derailments. Derailments on main and siding tracks accounted for 65% of freight train accidents and correspondingly 87% of the cars derailed on all types of track.

It is evident that the distribution of accident types varied by track type. For example, 98% of highway–rail grade crossing accidents occurred on main tracks, whereas far fewer occurred on yard tracks. A chi-square test was used to examine the association between track type (main, siding, yard, and industry) and accident type (derailment, collision, highway–rail grade crossing accident, and other) by accident frequency. The chi-squared test showed that the accident frequency distributions of different accident types varied by track type ($\chi^2 = 1,054$, df = 9, $P < .01$). This result was significant even when only derailment and collision were included in the analysis ($\chi^2 = 68$, df = 3, $P < .01$). The association between accident type and track type implies that different track types have different accident cause distributions, which will be discussed in the following sections. Train collisions and highway–rail grade crossing accidents have been analyzed in other recent studies, so this research focused on train derailments (5, 7, 8).

TRAIN ACCIDENT CAUSE

FRA train accident cause codes are hierarchically organized and categorized into major cause groups—track, equipment, human factors, signal, and miscellaneous. Within each of these major cause groups, FRA organizes individual cause codes into subgroups of

TABLE 1   Accident Frequency, Accident Severity, and Car Derailment by Accident Type
and Track Type, Class I Freight Railroads, 2001–2010

| | Accident Type | | | | |
Track Type	Derailment	Collision	Highway–Rail	Other	All Accident Types
Number of Freight Train Accidents					
Main	4,439	302	1,343	590	6,674
Yard	2,848	355	12	378	3,593
Siding	436	23	4	40	503
Industry	369	21	6	49	445
All	8,092	701	1,365	1,057	11,215
Average Number of Cars Derailed per Accident					
Main	8.4	3.3	0.5	1.0	5.9
Yard	4.7	1.5	0.8	1.4	4.0
Siding	5.7	3.7	0.0	1.2	5.2
Industry	4.3	1.0	1.3	0.5	3.7
All	6.8	2.3	0.5	1.1	5.2
Total Number of Cars Derailed					
Main	37,456	989	609	580	39,634
Yard	13,363	527	9	511	14,410
Siding	2,477	85	0	47	2,609
Industry	1,593	22	8	23	1,646
All	54,889	1,623	626	1,161	58,299

related causes, such as roadbed and track geometry, within the track group and similar subgroups within the other major cause groups. A variation on the FRA subgroups developed by Arthur D. Little, in which similar cause codes were combined into groups on the basis of expert opinion, was used (9, 10). The Arthur D. Little groupings are similar to FRA's subgroups but are more fine-grained, thereby allowing greater resolution for certain causes. For example, FRA combines broken rails, joint bars, and rail anchors in the same subgroup, whereas the Arthur D. Little grouping distinguishes between broken rail and joint bar defects. These groups were used to analyze cause-specific derailment frequency and severity. The cause groups are ranked in descending order by number of derailments and total number of cars derailed, respectively. The former metric pertains to derailment frequency, whereas the latter accounts for derailment frequency and severity. Different ranking methods may lead to different safety improvement prioritization decisions.

TRAIN DERAILMENTS

Derailments are the most common type of train accident in the United States, and preventing them has long been a focus of the rail industry and the government (1–3, 9–25). Most previous studies have focused on main-line derailments, with less research published on yard and siding derailments. The derailment-cause distribution on main lines differs from distributions on yard or siding tracks, in part because of the different nature of operations in these two settings. Understanding the top causes affecting train derailment occurrence and number of cars derailed on different tracks provides additional insight into the development, evaluation, prioritization, and implementation of accident prevention strategies given a specific set of operating conditions.

Derailments on Main Tracks

Although serious incidents can and do occur on yard and siding tracks, the focus of this research is on main-line derailments because of the higher speeds and longer consists typical of main-line operation. The greater mass and speed mean that the force and potential impact in regard to property damage, casualties, and environmental effects are all correspondingly greater. An analysis of derailment causes was conducted to compare the relationship between frequency and severity by derailment cause. Accounting for severity is important because derailments in which more cars are involved are likely to be more damaging and more costly, have a greater likelihood of involving a hazardous materials car if any are in the consist, and if derailed they are more likely to suffer a release (1). In addition to type of track, accident severity, as measured by number of cars derailed per accident, also varies by accident cause (Table 2). Accident severity is affected by a variety of factors, including train length (2, 16, 20), derailment speed (1–3, 13, 16, 17, 20, 25), point of derailment (POD) (the position of the first car in the train that is derailed) (2, 16), and other factors (11, 12). A number of studies have investigated the parametric relationships between accident cause and certain contributing factors affecting train derailment severity (2, 13, 16). The number of derailments and total number of cars derailed are directly related to train derailment rate and car derailment rate, respectively. The former represents the likelihood that a train is involved in a derailment and the latter the likelihood of an individual car derailing. Both rates are useful in risk assessment depending on the question being addressed (2, 3, 9, 13, 17, 19–25). The importance of either statistic can be used to rank the importance of a particular accident cause, and these were used to investigate the association between the two ranking methods (Table 2). A Spearman's rank correlation test showed that the two ranking methods were significantly related

TABLE 2 Derailment Frequency and Severity by Accident Cause on Class I Main Lines, Sorted by Frequency

Cause Group	Description	Derailments		Cars Derailed		Average Number of Cars Derailed per Derailment
		Number	Percentage	Number	Percentage	
08T	Broken rails or welds	665	15.3	8,512	22.7	12.8
04T	Track geometry (excluding wide gauge)	317	7.3	2,057	5.5	6.5
10E	Bearing failure (car)	257	5.9	1,739	4.6	6.8
12E	Broken wheels (car)	226	5.2	1,457	3.9	6.4
09H	Train handling (excluding brakes)	201	4.6	1,553	4.1	7.7
03T	Wide gauge	169	3.9	1,729	4.6	10.2
01M	Obstructions	153	3.5	1,822	4.9	11.9
05T	Buckled track	149	3.4	1,891	5.0	12.7
04M	Track–train interaction	149	3.4	1,110	3.0	7.4
11E	Other axle or journal defects (car)	144	3.3	1,157	3.1	8.0
03M	Lading problems	134	3.1	791	2.1	5.9
07E	Coupler defects (car)	133	3.1	771	2.1	5.8
13E	Other wheel defects (car)	129	3.0	668	1.8	5.2
09E	Sidebearing, suspension defects (car)	126	2.9	816	2.2	6.5
10T	Turnout defects: switches	118	2.7	601	1.6	5.1
11H	Use of switches	104	2.4	407	1.1	3.9
06E	Centerplate or carbody defects (car)	98	2.3	507	1.4	5.2
01H	Brake operation (main line)	95	2.2	881	2.4	9.3
12T	Miscellaneous track and structure defects	80	1.8	687	1.8	8.6
01T	Roadbed defects	67	1.5	665	1.8	9.9
07T	Joint bar defects	66	1.5	1,040	2.8	15.8
10H	Train speed	61	1.4	403	1.1	6.6
09T	Other rail and joint defects	56	1.3	1,132	3.0	20.2
19E	Stiff truck (car)	55	1.3	365	1.0	6.6
05M	Other miscellaneous	54	1.2	422	1.1	7.8
15E	Locomotive trucks, bearings, wheels	50	1.1	177	0.5	3.5
18E	All other car defects	47	1.1	248	0.7	5.3
06T	Rail defects at bolted joint	46	1.1	927	2.5	20.2
12H	Miscellaneous human factors	44	1.0	377	1.0	8.6
02T	Nontraffic, weather causes	43	1.0	331	0.9	7.7
02H	Handbrake operations	41	0.9	177	0.5	4.3
20E	Track–train interaction (hunting) (car)	40	0.9	419	1.1	10.5
05E	Other brake defect (car)	37	0.9	187	0.5	5.1
08E	Truck structure defects (car)	35	0.8	265	0.7	7.6
07H	Switching rules	30	0.7	198	0.5	6.6
02E	Brake rigging defect (car)	27	0.6	148	0.4	5.5
01E	Air hose defect (car)	19	0.4	148	0.4	7.8
01S	Signal failures	17	0.4	121	0.3	7.1
17E	All other locomotive defects	13	0.3	155	0.4	11.9
11T	Turnout defects: frogs	11	0.3	97	0.3	8.8
08H	Mainline rules	11	0.3	56	0.1	5.1
16E	Locomotive electrical and fires	10	0.2	28	0.1	2.8
04E	UDE (car or locomotive)	8	0.2	86	0.2	10.8
03H	Brake operations (other)	4	0.1	47	0.1	11.8
05H	Failure to obey or display signals	4	0.1	23	0.1	5.8
04H	Employee physical condition	3	0.1	41	0.1	13.7
06H	Radio communications error	3	0.1	13	0.0	4.3
14E	TOFC–COFC defects	2	0.0	2	0.0	1.0
03E	Handbrake defects (car)	1	0.0	2	0.0	2.0
	Total	4,352	100	37,456	100	8.6

NOTE: UDE = undesired emergency (brake application); TOFC = trailer on flat car; COFC = container on flat car.

(Spearman rho = 0.95, $P < .01$). Certain derailment causes, notably broken rails or welds, are the most frequent when using either metric; consequently, efforts to prevent these high-frequency, high-severity accidents receive considerable attention.

Derailment frequency and severity (average number of cars derailed) were plotted against one another, with frequency on the abscissa and severity on the ordinate (Figure 1). The graph is divided into four quadrants on the basis of the average derailment frequency and severity along each axis. The graph enables easy comparison of the relative frequency and severity of different causes. Those causes 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. The five cause groups are

- Broken rails or welds,
- Wide gauge,
- Buckled track,
- Obstructions, and
- Main-line brake operation.

Four other cause groups that are notable because of their high frequency of occurrence are

- Track geometry (excluding wide gauge),
- Bearing failure (car),

- Broken wheels (car), and
- Train handling (excluding brakes).

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

- Rail defects at bolted joints,
- Other rail and joint defects, and
- Joint bar defects.

These three causes, along with the related cause group, broken rails or welds, are of particular interest, because when combined they accounted for almost 20% of all derailments and more than 30% of all derailed cars on Class I main lines (Table 2).

Derailments on Siding and Yard Tracks

As discussed above, main track derailments are likely to be the most serious, but understanding the causes of derailments on siding and yard tracks is worthwhile because certain causes and solutions may apply to both. A chi-square test was conducted to compare the distributions of derailment frequency by the top 20 main-line derailment causes on main, yard, and siding tracks. The distribution of
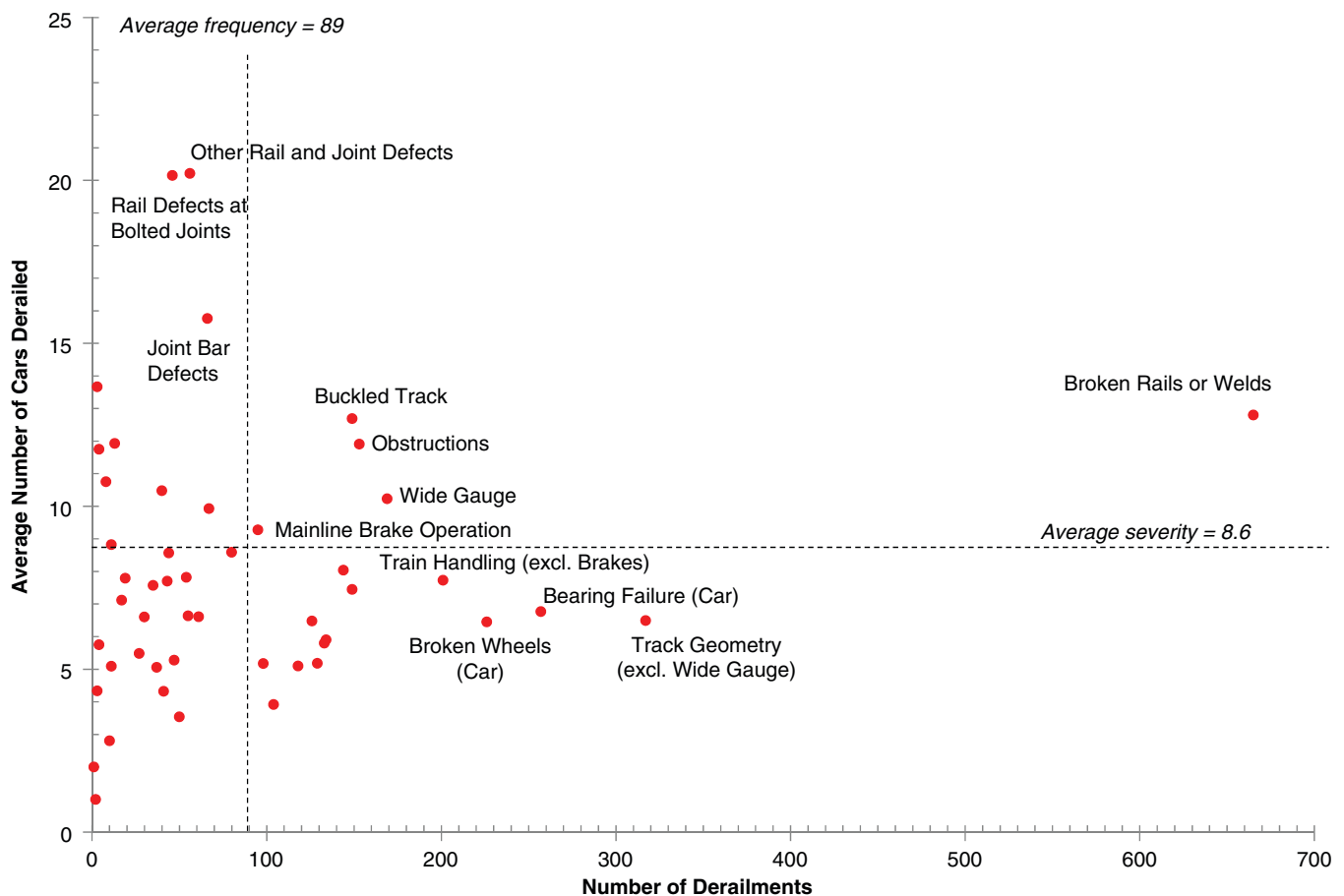

FIGURE 1 Frequency and severity graph of Class I main-line freight train derailments, 2001–2010.

TABLE 3 Top 10 Accident Causes of Freight Train Derailments by Track Type: Number of Derailments

	Freight Train Derailments					
	Main		Siding		Yard	
Rank	Cause Group	Percentage	Cause Group	Percentage	Cause Group	Percentage
1	Broken rails or welds	15.3	Broken rails or welds	16.5	Broken rails or welds	16.4
2	Track geometry (excluding wide gauge)	7.3	Wide gauge	14.2	Use of switches	13.5
3	Bearing failure (car)	5.9	Turnout defects—switches	9.7	Wide gauge	13.5
4	Broken wheels (car)	5.2	Switching rules	7.7	Turnout defects—switches	11.1
5	Train handling (excluding brakes)	4.6	Track geometry (excluding wide gauge)	7.2	Train handling (excluding brakes)	6.7
6	Wide gauge	3.9	Use of switches	5.8	Switching rules	6.2
7	Obstructions	3.5	Train handling (excluding brakes)	3.5	Track geometry (excluding wide gauge)	3.6
8	Buckled track	3.4	Lading problems	2.3	Miscellaneous track and structure defects	3.4
9	Track–train interaction	3.4	Roadbed defects	2.1	Track–train interaction	3.1
10	Other axle or journal defects (car)	3.3	Miscellaneous track and structure defects	2.1	Other miscellaneous	3.0

derailment causes varied significantly by track type ($\chi^2 = 1{,}780$, df = 38, $P < .01$). Tables 3 and 4 show the top 10 accident causes by derailment frequency and total number of cars derailed, respectively, on different track types.

Comparison of main tracks with yard and siding tracks using either metric, derailment frequency or number of cars derailed, reveals that broken rails or welds were the leading derailment cause on all three track types. However, by contrast to main tracks, bearing failures and broken wheels were not among the top accident causes on yard and siding tracks, probably because of lower operating speeds. Instead, human factor–related causes such as improper use of switches and violation of switching rules were more prevalent. Misaligned switches caused 14% of yard derailments, and this cause has received particular attention in recent years. The higher incidence

TABLE 4 Top 10 Accident Causes of Freight Train Derailments by Track Type: Number of Cars Derailed

	Freight Cars Derailed Because of Train Derailments					
	Main		Siding		Yard	
Rank	Cause Group	Percentage	Cause Group	Percentage	Cause Group	Percentage
1	Broken rails or welds	22.7	Broken rails or welds	23.2	Broken rails or welds	19.3
2	Track geometry (excluding wide gauge)	5.5	Wide gauge	13.8	Wide gauge	18.2
3	Buckled track	5.0	Turnout defects—switches	10.4	Use of switches	10.0
4	Obstructions	4.9	Track geometry (excluding wide gauge)	6.2	Turnout defects—switches	9.8
5	Bearing failure (car)	4.6	Use of switches	4.8	Train handling (excluding brakes)	7.7
6	Wide gauge	4.6	Switching rules	4.0	Miscellaneous track and structure defects	4.2
7	Train handling (excluding brakes)	4.1	Train handling (excluding brakes)	3.5	Switching rules	3.9
8	Broken wheels (car)	3.9	Obstructions	3.0	Track geometry (excluding wide gauge)	3.3
9	Other axle or journal defects (car)	3.1	Buckled track	2.8	Track–train interaction	3.2
10	Other rail and joint defects	3.0	Brake operation (main line)	2.7	Brake operation (main line)	2.7

of switch-related derailments in yards and sidings compared with main lines is probably due to the greater number and more frequent use of turnouts on these tracks and thus the greater likelihood of error. Another consequence of the more frequent use of switches is the greater prevalence of switch defects. Switch defects caused approximately 10% of derailments on yard and siding tracks, but only 3% on main lines. The reason for this is probably twofold: the more frequent use of switches on these types of tracks subjects them to greater exposure and thus more opportunity to cause a derailment, and because of their heavy use, the switches are subject to more wear and tear and consequently faster deterioration. The switch points are typically the most vulnerable parts of switches, so their protection and lubrication, along with improved wheel profile and truck steering performance, may offer means to prevent switch-defect derailments (26–28). Another difference between main tracks compared with yard and siding tracks is that wide gauge accounted for 14% of derailments on siding and yard tracks but for only 4% on main lines. Again, this difference is probably due to the lower speed characteristic of yard and siding tracks but with a different explanation; the lower operating speed permits greater tolerances in the

track gauge standards, and therefore these tracks may be more prone to this type of derailment (29).

EFFECT OF DERAILMENT SPEED

So far this paper has considered accident and track type as factors affecting the likelihood that a train or rail car will derail, but another important parameter affecting derailments is train speed at the time of derailment. Indeed, speed may be a contributing factor to some of the differences cited above. Common sense demands that speed is a factor affecting derailment severity, and previous research has established several qualitative and quantitative relationships between derailments and speed (1). The top 10 accident causes of main-line train derailments were sorted into different groups, corresponding to the FRA track class speed ranges, and compared, again by derailment frequency and number of cars derailed (Figure 2) (29).

In all speed ranges, broken rails or welds were the leading cause of derailments; however, the relative frequency of the next most common accident types differed substantially for lower versus
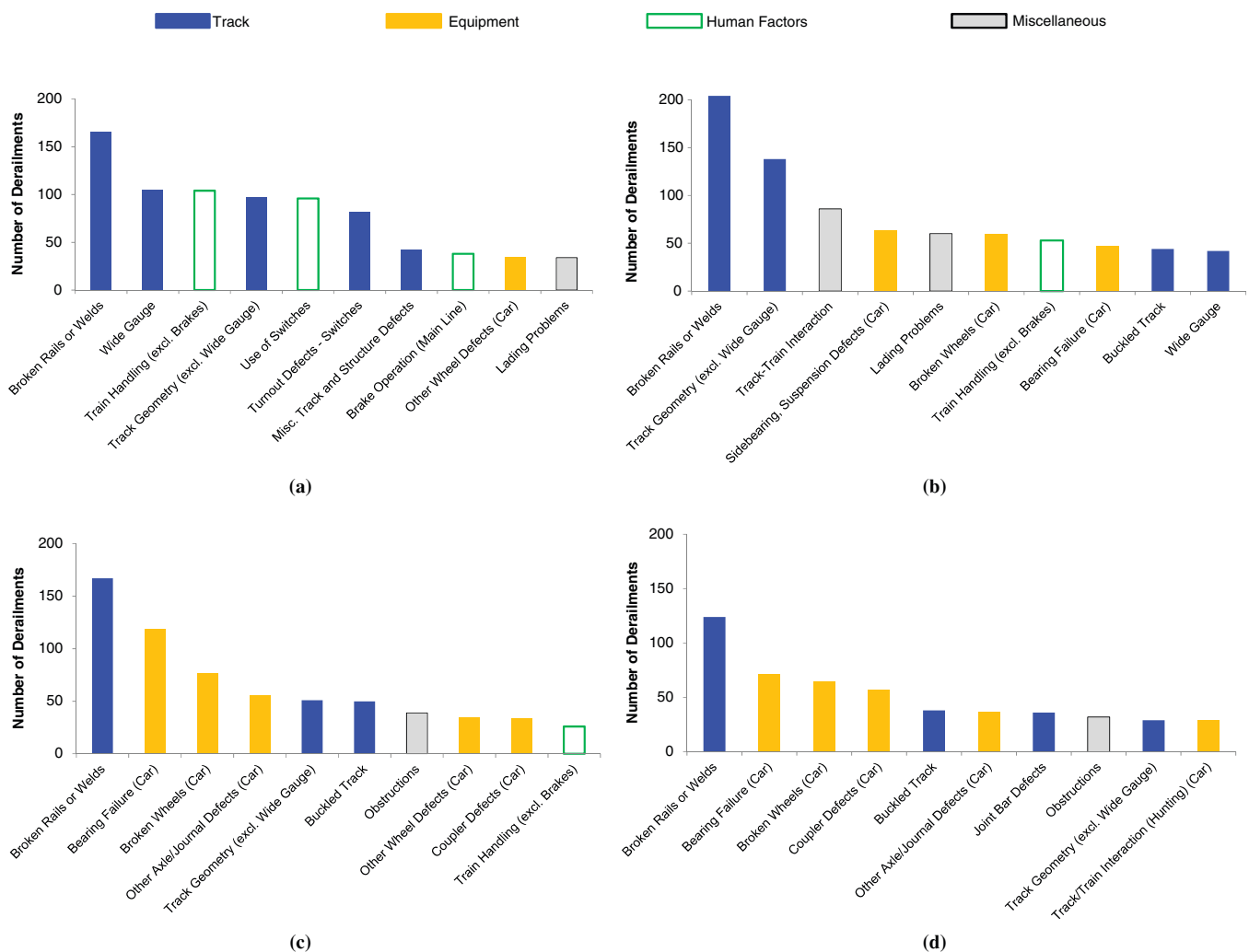

FIGURE 2   Number of freight train derailments by speed and accident cause on Class I main lines: (a) derailment speed 0–10 mph, (b) derailment speed 10–25 mph, (c) derailment speed 25–40 mph, and (d) derailment speed 40–80 mph.

higher speed derailments. At speeds below 10 mph, certain track-related and human factor–related causes occurred more frequently than equipment-related causes. But at derailment speeds greater than 25 mph, human factors accidents such as improper train handling, braking operations, and improper use of switches were almost completely absent, replaced by equipment causes, such as bearing failure, broken wheel, and axle and journal defects. The derailment frequency distribution for 49 main-line accident causes and three derailment-speed groups (<10 mph, 11–25 mph, and >25 mph) were compared in a chi-square analysis, and the results were significant ($\chi^2 = 1{,}192$, df = 96, $P < .01$), indicating an association between accident cause and derailment speed.

ACCIDENT PREVENTION STRATEGY

To gain insights into the potential safety benefits of strategies to reduce various types of derailments, a sensitivity analysis was conducted (Figure 3, *a* and *b*). An estimation was done to determine by what percentage main track train and car derailment rates would be reduced in the event that certain accident causes were reduced or eliminated. Four of the leading main-line accident causes were considered: broken rails or welds (08T), track geometry defects (04T), bearing failure (10E), and broken wheels (12E). There are a number of approaches in practice or being developed that may address these. Broken rail preventive measures include rail inspection, rail grinding, rail repair,
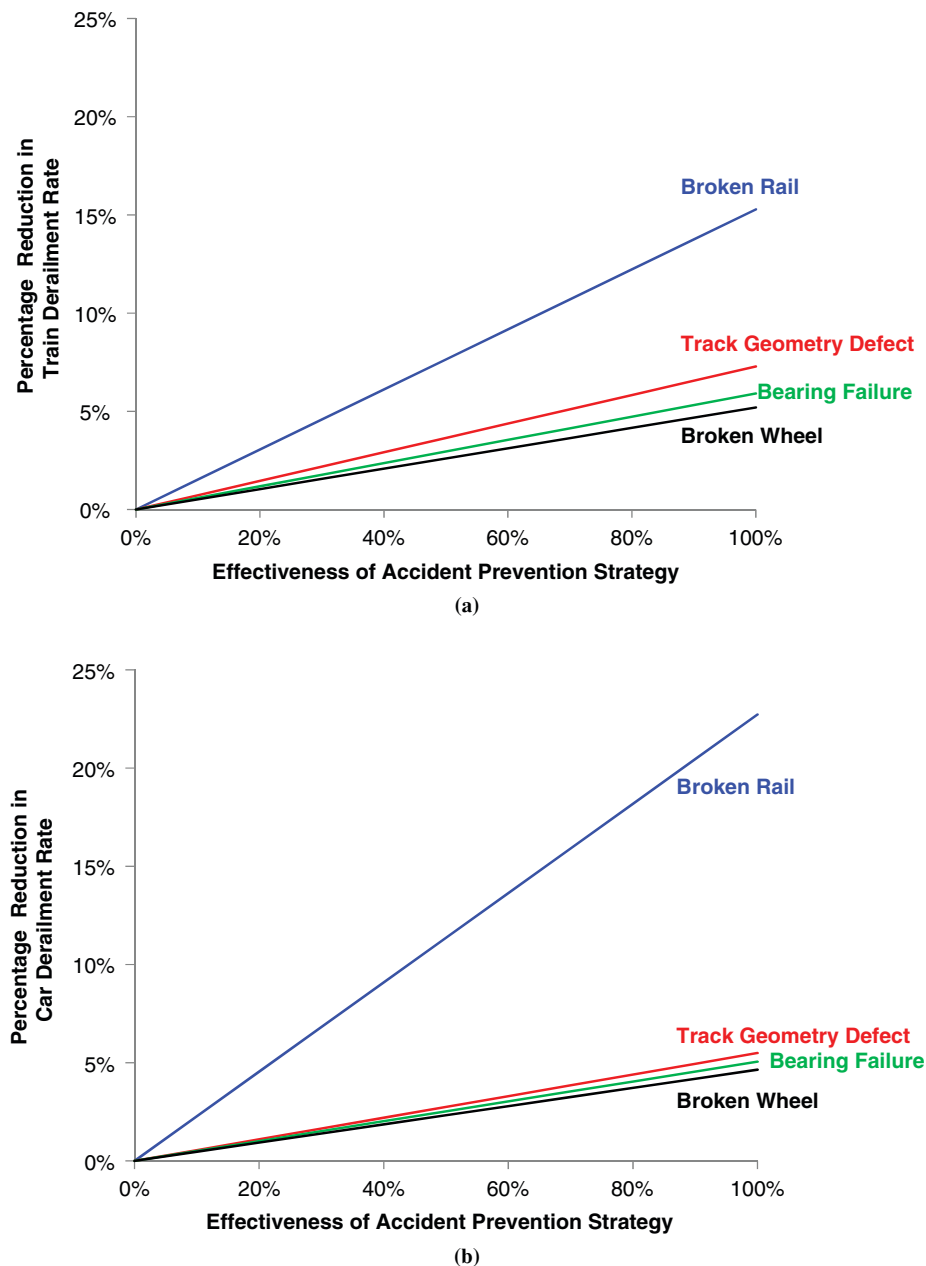

FIGURE 3   Percentage reduction in derailment rates by derailment prevention strategy: (*a*) train derailment rate reduction and (*b*) car derailment rate reduction.

and renewal (*30*). Track geometry inspection and maintenance are often based on some measurable indices, such as the track quality index (*31, 32*). Wayside and onboard detection systems aim to identify and inform railroads and car owners about the need to remove or repair rolling stock defects before they cause an accident. Hot bearing detectors and wheel impact load detectors are commonly used to detect problems with those components (*33, 34*). Nevertheless, these techniques and technologies are not 100% effective in eliminating all the accident causes they are intended to prevent, and research and development are ongoing to further develop their capability. The effectiveness of an accident prevention strategy is defined here as the percentage of the maximum safety benefit it might potentially realize. The sensitivity analysis helps illustrate the relevant potential safety benefit that might be realized if technologies or techniques were implemented with varying degrees of effectiveness. For example, broken rails or welds caused 15.3% of train derailments and 22.7% of cars derailed (Table 2); thus, if all broken-rail-related causes were eliminated, train and car derailment rates would decline by a corresponding amount. Even if only 50% of broken rails or welds could be prevented, the prevention would result in a larger percentage reduction in train and car derailment rates than would any of the other accident prevention strategies at 100% effectiveness.

The effects of different accident prevention strategies may not necessarily be independent of one another. For example, improved wheel condition can reduce dynamic loading of track, thereby reducing track defect rates, and vice versa. The interactive damage forces between track and equipment have been discussed in previous studies (*35, 36*). Resor and Zarembski proposed an engineering model to estimate the change in relative damage to track and equipment given the change in impact load (*35*). With the use of their model, it was estimated that a 1% reduction in impact load would result in a 1.3% reduction in damage to track and a 0.6% reduction in damage to wheels and axles. Nevertheless, the authors are unaware of any research that quantifies the reduction in track and equipment damages, with the corresponding reduction in accident probability. Further research is needed to understand better what the possible interactive effects are, how to quantify them where they exist, and what their effects are on accident rate estimation and safety policy evaluation. For purposes of illustration, independence of individual derailment prevention strategies was assumed in the sensitivity analyses presented here. To the extent that interactive effects among different accident prevention strategies reduce the safety benefits due to another, the analyses here may slightly overstate the benefit of a particular derailment cause prevention measure if other related measures were implemented.

This paper focuses on developing an analytical framework to understand the relative importance of different accident causes under various operating conditions. The analyses presented here are just the first step in a risk-based approach to derailment prevention. The implementation costs of different risk reduction measures may be affected by the effectiveness of technology, extent of implementation, installation and maintenance practices, and many other factors. Schafer and Barkan estimated $900 per track mile as the annual cost for ultrasonic and geometric track inspection and $1,900 per track mile for rail grinding on one Class I railroad (*30*). Robert et al. reported a total cost of $86 million for implementing wayside detectors in the United States from 1994 to 2008 (*37*). However, the proportion of the costs directly related to safety improvement is not well understood and further study is required. An additional complexity is that safety improvement activities may affect operational efficiency differently in different time periods. For example, track maintenance may cause

train delay in the short term but improve efficiency in the long term by reducing the potential service disruptions due to accidents.

Further research is needed to understand the relationship between accident rates and occurrence in regard to accident frequency and corresponding traffic exposure. This research will enable a better comparison of the accident risk under different operating conditions, such as main lines versus yard tracks. The next step is to quantify the benefits and costs of specific risk reduction measures, thereby allowing integration of the multiple trade-offs involving safety, efficiency, and cost. In that way, interactive effects between strategies can be accounted for, and the optimal combination of investment strategies selected for any given level of financial resources.

CONCLUSIONS

Accident cause distribution varies by accident type, track type, and speed. Derailments are the most common type of train accident on each track type, and the majority of cars derailed are due to train derailments. Track and equipment failures are the primary causes of train derailments on main tracks, whereas the use of switches and switching rules has a substantial effect on derailment frequency on siding and yard tracks. Some accident causes tend to occur more frequently at higher speeds, whereas others are more likely at lower speeds. The interactive effects of derailment speed and accident cause affect train accident frequency and severity.

The safety benefits of accident prevention strategies were evaluated according to the percentage reduction in train and car derailment rates. Prevention of broken rails or welds is expected to yield a larger percentage reduction in train and car derailment rates than other accident prevention strategies. However, the cost-effectiveness of this and other accident prevention strategies must be properly compared to select the most efficient means of improving railroad train operating safety. Ultimately these strategies should be considered as part of an integrated framework to optimize investment that maximizes safety benefits and minimizes risk.

ACKNOWLEDGMENTS

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The Railroad Operational Safety Committee peer-reviewed this paper.