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Quantitative causal analysis of mainline passenger train accidents in the United States

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Abstract

The need for shared freight and passenger rail corridors in the United States is increasing due to the growing demand for regional and intercity passenger transport. Several researches have been conducted on reducing the risk of freight train accidents, but little research has been done on the risk of passenger train accidents. The accident rates of passenger trains have declined in the past two decades; however, faster and more frequent passenger train services require even higher safety standards, and therefore further reduction to the risk of passenger train accidents is needed. The research presented in this paper analyzed the passenger train accidents in the United States using the Federal Railroad Administration train accident database to understand the trend of passenger train accident rates, the frequency and severity of different types of accidents, and to explore the major factors that cause them. Derailments and collisions were identified as the most significant types of passenger train accidents, and track failures and human factors, respectively, were the primary causes of those accidents. Accidents caused due to human factors and train operations such as train speed violations and failure to obey signals are often high-consequence accidents and therefore pose the greatest risk. Higher risk infrastructure-related factors include track geometry defects and broken rails or welds. This study on passenger train accidents provides a solid foundation for further research on improving the safety of passenger rail and shared-use rail corridors.

Keywords

Passenger rail safety, train accident, train derailment, train collision, risk analysis, causal analysis

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Introduction

Increasing demand for passenger rail transport in the United States (Figure 1) has led to the growth of faster and more frequent passenger rail services. Funding and legislative support for the improvement of the existing passenger rail services and new passenger rail corridors have been provided by the federal government.[1–6] High-level rail transportation plans have also been proposed at the state level to achieve these goals.[7–12] The high-speed rail project in California is now under construction,[13] and the high-speed rail project in Texas is in its planning process.[14] Speed, frequency, and service improvement projects are being implemented to achieve higher speed rail corridors in the Midwest and on the Northeast Corridor.[15] New intercity passenger rail services have also been constructed or proposed in Florida,[16] Massachusetts,[17] and other states.[15,18] In addition, transit and regional passenger rail systems are being improved or expanded.[19–22]

Two approaches are being used to carry out these passenger rail projects and initiatives: incremental upgrade of the existing railroad infrastructure and construction of new, dedicated passenger rail lines.[24] Both approaches lead to the development of shared-use rail corridors (SRCs) where passenger trains share the track, right-of-way or railroad corridors with freight trains and other types of passenger trains.[25,26] The majority of commuter and intercity passenger trains operate on or next to freight railroad

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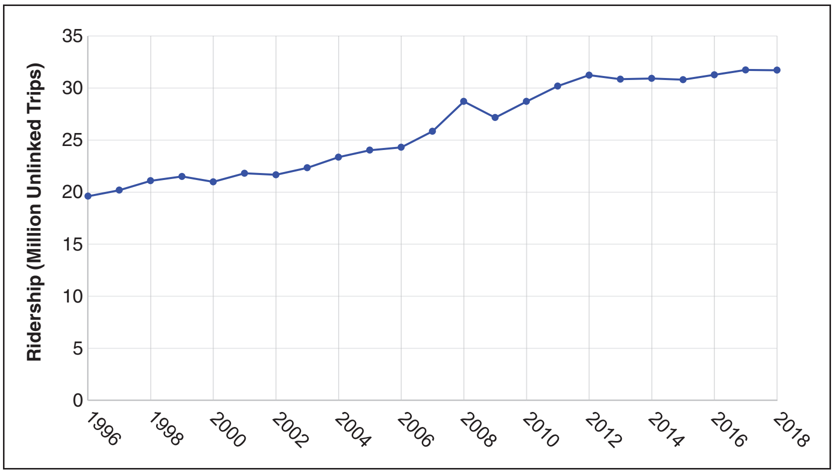

Figure 1. Amtrak ridership by million unlinked trips: 1996–2018.[23]

corridors.[27] While these SRCs offer benefits such as lower capital costs, less economic, environmental and social impact, and easier accessibility to core urban areas,[28] they also raise safety concerns due to more frequent, higher speed operations of passenger trains in close proximity to freight trains and maintenance-of-way personnel.[29] As service and ridership grow, so do the safety and risk implications. Understanding these aspects of passenger train operations is essential for better resource allocation to improve the safety of passenger trains and reduce the risk of accidents and casualties.

Literature review

Research on the analyses of train accidents in the United States has focused primarily on freight train derailments,[30–39] hazardous material releases,[40–48] and grade crossing incidents.[49–56] Relatively few studies have focused on the quantitative analysis of the safety of U.S. passenger trains. Much of the existing research investigated the damage resistance ability of the passenger rail equipment and the crash energy management systems. These systems are intended to reduce casualties during a train collision or derailment.[57–61] Lin et al.[62] conducted a fault tree analysis to identify major factors that could lead to an adjacent track accident on SRCs. Lin and Saat[63] developed a semi-quantitative risk assessment model to evaluate the adjacent track accident risk and identified factors that affect the train intrusion probability.

Internationally, there have been more quantitative studies of passenger train accidents. Niwa[64] analyzed five major aspects of Japanese railway accidents (liveware-person concerned, liveware-other personnel, hardware, software, work place) and conducted case studies of several severe accidents. Ouyang et al.[65] used the System Theoretic Accident Model and Process (STAMP) to analyze a disastrous railway accident on the Jiaoji Railway in China. Chen et al.[66] used the Associated Rule and other data mining techniques to analyze Chinese passenger train accidents. Britton et al.[67] conducted a causal analysis of train derailments in Australia.

Quantitative studies of passenger rail safety have also been conducted in Europe. Evans[68] conducted a statistical analysis of fatal train accident trends on the British railways. The author proposed an exponential function to predict the declining trend of train accident rates and applied it to other mainline railway systems in Japan, Britain, and Europe.[69–71] Silla and Kallberg[72] studied the development of railway safety in Finland and Santos-Reyes, and Beard[73,74] used the Safety Management System model to analyze two major passenger train accidents in the United Kingdom.

These studies provide insights into the accident analysis methodologies and results for reference and comparison; however, there are a number of differences in operating practices, rolling stock, and organizational structure that affect passenger train safety in the U.S. environment. This is especially so in the context of North American SRCs where heavy-axle-load freight trains are the norm but are rare on most other nations' rail systems. On many European and Asian rail networks, passenger trains outnumber freight trains and most trains operate on fixed schedules. By contrast, in North America, freight trains are the dominant type and these trains are much longer, are comprised of much heavier freight cars, and operate on flexible schedules.[75] Another difference is the design of passenger rolling stock. In Europe and Asia, passenger cars are of lighter weight and run at higher speeds with more rapid acceleration and deceleration. In North America, passenger rail equipment is heavier because it must meet the robust crashworthiness standards set by the U.S. Federal Railroad Administration (FRA) because of possible collisions with heavy locomotives and freight cars in accidents.[59] Consequently, results from previous research on passenger train accidents in other parts of the world are not directly transferrable to the U.S.

rail environment. Further study of passenger train accidents is necessary to understand how to most effectively manage and reduce the risk associated with U.S. passenger train operation.

Research objective

In this paper, we present an analysis of mainline passenger train accidents in the United States from 1996 to 2017. The objective is to understand the general trend of mainline passenger train accident rates, quantify the frequency and severity of different accident types, and identify the major factors that cause them. In addition, the potential effect of positive train control (PTC) and train speed on passenger train accident risk, and the implications of passenger train accident analysis to SRC risk management are explored.

Analysis of passenger train accidents, 1996–2017

Train accident data from the United States Department of Transportation (USDOT) FRA were used for the analysis.[76] Railroad accidents/incidents that result in monetary loss exceeding a specified threshold must be reported to the Rail Equipment Accident (REA) database maintained by the FRA.[77] This threshold is periodically adjusted for inflation and is low enough so that only relatively minor incidents are not included. The FRA categorizes train accidents into 13 types. For the purpose of analysis, these 13 types were consolidated into five accident categories: derailment, collision, obstruction, grade crossing incidents, and miscellaneous. Incidents caused by defective pantograph or overhead catenary system occur relatively infrequently, and although such incidents can cause large monetary damage to railroad infrastructure and equipment and thus must be reported, they pose relatively little hazard to onboard passengers and crew. Therefore, these incidents were not included.

Passenger train accident rate is calculated as the number of accidents per million passenger train miles (APMPTM). In 1996, there were 0.99 APMPTM. In 2017, the most recent year for which data were available, this figure had dropped to 0.90 APMPTM (Table 1). During the intervening years this rate fluctuated widely, peaking at 1.075 APMPTM in 2004 (Figure 2(a)).

To understand what was affecting the rate, the data were broken down by the five accident categories defined (Figure 2(b)). The fluctuations appear to be driven primarily by grade crossing and obstruction accidents, both of which are largely outside of railroads' control. Derailments and collisions showed a weak but generally downward trend. This is consistent with the downward trend of mainline freight train derailment and collision rates, although the freight railroad trend is more obvious (and in fact, statistically significant).[38,78]

Miscellaneous accidents were uncommon and showed no evident trend. Perhaps the most interesting pattern observed is the contrast between the passenger train and freight train grade crossing accident rate, which has steadily declined over the same time period.[52,79] In the past two years the passenger train accident rate has increased, primarily due to an increase in grade crossing and obstruction accidents. Whether this is simply due to random fluctuation associated with the relatively small number of accidents, or indicative of an actual increasing trend is not known.

A time series analysis was conducted for the different types of passenger train accident data (Table 2). Negative binomial and Poisson regressions were used to fit the data, and passenger train traffic and time trending factors were selected as parameters to be estimated. The Akaike information criterion (AIC)[80] and Bayesian information criterion (BIC)[81] methods were used to determine which regression model provided a better fit to the data. Results show that no particular temporal trend was evident for the different types or for the overall total. Passenger train traffic has increased over the analysis period as suggested above (Table 1); however, the effect of passenger train traffic is not statistically significant in most of the categories with the exception of obstruction incidents. This suggests that the increase in passenger train traffic over time does not appear to be related to the increase or decrease of passenger train accident rates.

Risk is generally defined as the probability of a particular event multiplied by its consequence.[82] To identify the types of accidents that pose the greatest threat (i.e. high probability, consequence, or both), accident rates and severity for each category of mainline passenger train accident were plotted in a frequency–severity graph (Figure 3). Frequency–severity graphs are a helpful risk visualization tool for train accidents because they enable comparison of the relative frequency and severity of different accident types. They have been used in a number of other railroad accident analyses.[33,36,83,84] The graph is divided into four quadrants on the basis of average frequency (AF) and average severity (AS) along each axis.

Frequency in this graph is defined as the train accident rate. Several different variables were considered to measure the passenger train accident severity. The number of railcars derailed has often been used as a proxy variable to measure the freight train accident severity.[33,37,43,46,84] For passenger trains, casualties are another important metric of accident severity.[62,66,68–71] In this research, casualties are defined as the total number of onboard passenger and crew injuries and fatalities, and were used as the primary severity indicator.

Table 1. Annual number of FRA-reportable mainline passenger train accidents by accident category, 1996–2017.

		Derailment		Collision		Grade crossing		Obstruction		Miscellaneous		Total	
Year	Traffic[a]	Accident	Rate	Accident	Rate	Accident	Rate	Accident	Rate	Accident	Rate	Accident	Rate
1996	77.0	22	0.286	3	0.039	30	0.390	19	0.247	2	0.026	76	0.987
1997	78.0	16	0.205	1	0.013	30	0.384	14	0.179	0	0.000	61	0.782
1998	78.4	10	0.128	1	0.013	13	0.166	14	0.179	1	0.013	39	0.498
1999	82.4	6	0.073	3	0.036	22	0.267	10	0.121	1	0.012	42	0.510
2000	84.3	15	0.178	2	0.024	24	0.285	17	0.202	2	0.024	60	0.712
2001	87.8	13	0.148	6	0.068	12	0.137	16	0.182	0	0.000	47	0.536
2002	89.6	10	0.112	6	0.067	20	0.223	13	0.145	0	0.000	49	0.547
2003	89.4	15	0.168	0	0.000	28	0.313	17	0.190	0	0.000	60	0.671
2004	89.3	10	0.112	6	0.067	53	0.593	26	0.291	1	0.011	96	1.075
2005	89.9	11	0.122	3	0.033	46	0.512	28	0.311	0	0.000	88	0.979
2006	92.0	13	0.141	3	0.033	33	0.359	18	0.196	0	0.000	67	0.729
2007	95.3	16	0.168	4	0.042	29	0.304	22	0.231	0	0.000	71	0.745
2008	98.1	12	0.122	4	0.041	37	0.377	11	0.112	0	0.000	64	0.653
2009	102.9	11	0.107	3	0.029	30	0.291	23	0.223	1	0.010	68	0.661
2010	104.1	10	0.096	2	0.019	33	0.317	19	0.182	0	0.000	64	0.615
2011	109.1	10	0.092	3	0.028	36	0.330	20	0.183	0	0.000	69	0.633
2012	107.5	11	0.102	0	0.000	31	0.288	11	0.102	0	0.000	53	0.493
2013	110.7	10	0.090	2	0.018	36	0.325	14	0.126	0	0.000	62	0.560
2014	112.3	10	0.089	3	0.027	31	0.276	11	0.098	0	0.000	55	0.490
2015	108.1	7	0.065	4	0.037	30	0.278	18	0.167	0	0.000	59	0.546
2016	110.5	9	0.081	2	0.018	52	0.470	21	0.190	0	0.000	84	0.760
2017	112.6	14	0.124	0	0.000	50	0.444	31	0.275	6	0.053	101	0.897
Total		261	0.138	61	0.032	706	0.374	393	0.208	14	0.007	1435	0.761

[a]Million passenger train miles.

To distinguish the difference in severity implied by injuries and fatalities, the fatality weighted index (FWI) was used. The FWI assigns different weights to a fatality, a major injury, and different levels of minor injuries.[85] Weights for each category differ by approximately an order of magnitude: one fatality is equivalent to 10 major injuries, 200 reportable minor injuries, and 1000 nonreportable minor injuries. FWI has been used in train accident analyses involving human injuries and fatalities.[86,87] There are only two levels of severity for onboard passengers and crew recorded in the FRA REA database: a person is either injured or fatally injured. Therefore, a 10:1 ratio was assigned to a fatality, meaning that one fatality was equivalent to 10 injuries.

Accident categories in the upper-right quadrant of the frequency–severity graph are the most likely to pose the greatest risk because they are both more frequent, and more severe, than average. None of the five accident categories fell in this quadrant, but derailments and collisions were most likely to result in high-casualty incidents. Together, they accounted for about 22% of passenger train accidents, but caused about 63% of total casualties (Table 3). Derailments and collisions also caused more damage to rail equipment and infrastructure and were more likely to result in onboard passenger and crew casualties. Although grade crossing incidents had the highest frequency, they were among the least severe in terms of consequences to onboard passengers and crew. Obstruction incidents, in which trains collide with foreign objects such as trees, boulders, or vehicles that are not at grade crossings, also had above-average frequency and low severity (Table 4). With few exceptions, obstruction incidents were less likely to cause severe onboard passenger and crew casualties. Therefore, the rest of this paper will examine mainline passenger derailments and collisions in more detail.

Causal analysis for passenger train derailment and collision accidents

To further understand which factors contributed the most to passenger train derailments and collisions, a causal analysis[33,35,36] was conducted. When a railroad reports a train accident, they identify the cause using predefined FRA cause codes.[88] There are two types of accident causes in the FRA accident reporting system: primary cause and contributing cause. A primary cause is the most direct cause leading to the occurrence of the accident, and a contributing cause is a factor that may have directly or indirectly led to the accident but was not as important as the primary

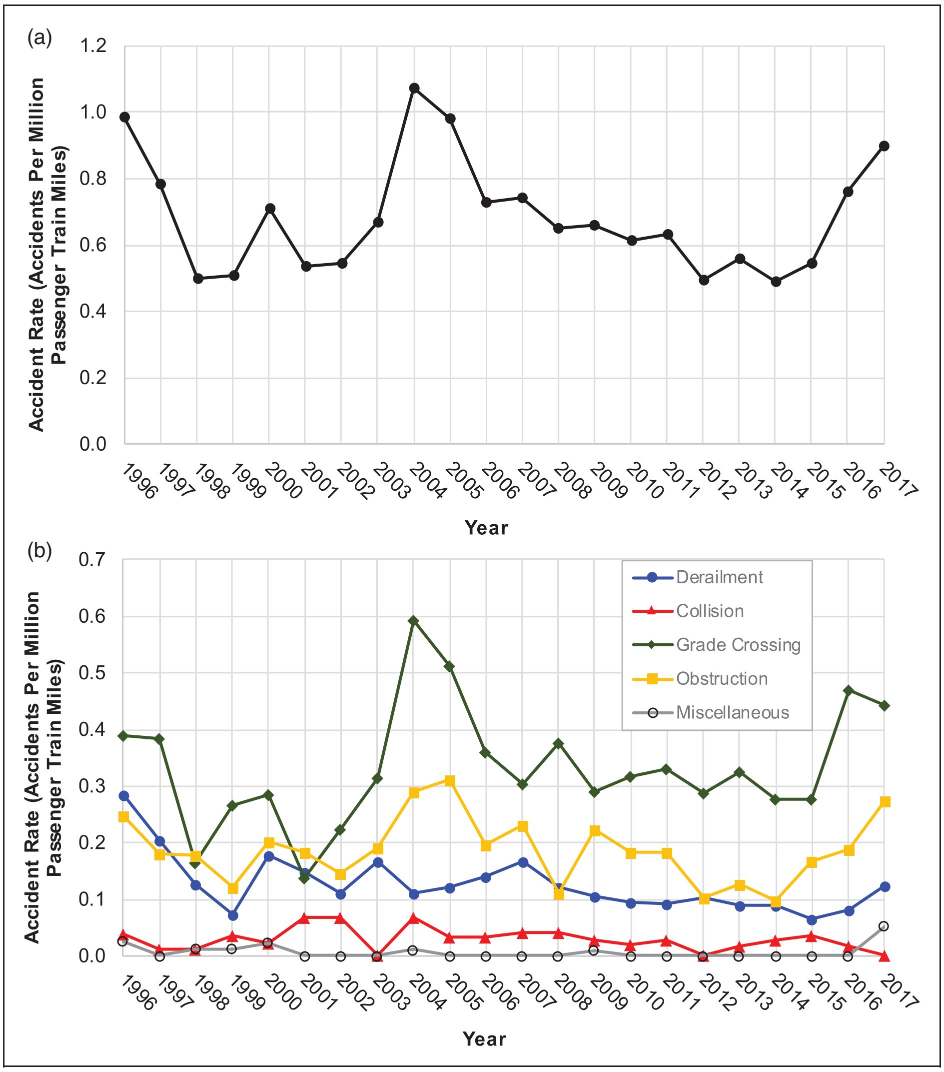

Figure 2. FRA-reportable mainline passenger train accident rates, 1996–2017: (a) overall rates; (b) rates by accident category.

cause. The FRA's accident reporting system allows one primary cause code entry and one contributing cause code entry. In some cases, two cause codes may be equally important. In these cases, the determination of which one is considered as the primary cause is left to the accident reporting personnel's best judgment. In some cases, when the primary cause code for an accident is clear, but multiple contributing causes were identified, the most relevant or appropriate one is reported.

Railroad accidents usually result from two types of causes: direct causes and underlying causes. Examples of the former include failure to obey signals, broken rail, broken wheel, and signal equipment failure. Underlying causes do not directly cause an accident but may foster an environment that makes an operation more prone to train accidents. Some examples of underlying causes are: engineer (train driver) fatigue,[89–91] insufficient maintenance of infrastructure or rolling stock,[92] and poor safety culture in an organization.[93,94] The FRA accident-cause codes capture most direct causes but are not as effective in identifying underlying causes. Some causes can be both a direct and an underlying cause of an accident, but in the FRA's reporting system, those causes are primarily used as the former (for example, engineer fatigue). In this analysis, the primary accident-cause codes of passenger train derailments and collisions were used to plot the frequency–severity graph.

FRA train-accident-cause codes are hierarchically organized and categorized into major cause groups: track (infrastructure), equipment (rolling stock), human factor, signal, and miscellaneous.[88] Each of these major cause groups has subgroups that include individual codes for related causes. The adjusted FRA subgroups developed by Arthur D. Little (ADL) and the Association of American Railroads (AAR) were used.[95] The ADL-AAR system groups similarly cause codes that enable greater resolution for certain train accident causes.[84] For example, FRA combines broken rails, joint bars and rail anchors in the same subgroup, whereas the ADL grouping distinguishes between broken rail and joint bar defects.[36]

Table 2. Time series analysis of FRA-reportable mainline passenger train accident by accident category, 1996–2017.

Type of accident	Derailment	Collision	Grade crossing
Fitted model	Poisson	Poisson	Negative binomial
Intercept	2.85	−0.33	21.40
Traffic	−2.14E−09	2.07E−08	1.31E−10
t-statistic	−7.78E−02	3.66E−01	1.32E−04
Time trending variable	−1.53E−02	−5.55E−02	9.56E−01
t-statistic	2.94E−01	5.16E−01	5.09E−01
Log-likelihood	−55.5	−43.0	−79.9
AIC	117.0	91.9	167.7
BIC	120.3	95.2	172.1
Type of accident	Obstruction	Miscellaneous	Total
Fitted model	Poisson	Negative binomial	Negative binomial
Intercept	6.69	0.55	55.10
Traffic	−5.30E−08	3.23E−12	1.00E−08
t-statistic	2.43E+00	2.54E−11	6.58E−09
Time trending variable	1.10E−01	7.62E−03	8.87E−01
t-statistic	2.70E+00	3.16E−02	3.08E−01
Log-likelihood	−65.8	−23.3	−89.9
AIC	137.6	54.6	187.8
BIC	140.9	59.0	192.1
Number of samples (years) (*n*)	22		
Number of coefficients (*k*)	4		
Degree of freedom ($n-k-1$)	18		
5% Critical value for the t-statistic	2.552		
1% Critical value for the t-statistic	1.734		

AIC: Akaike information criterion; BIC: Bayesian information criterion.

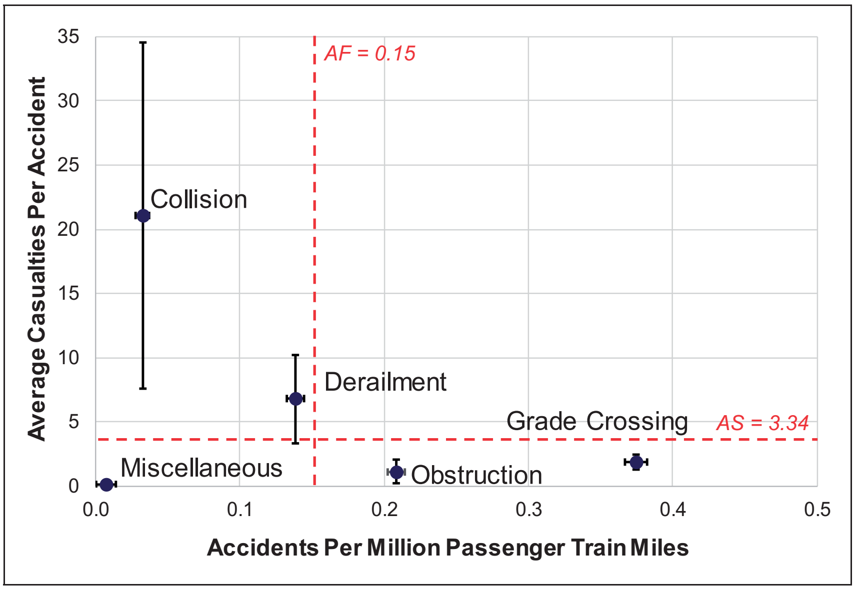

Figure 3. Frequency–severity graph for FRA-reportable mainline passenger train accidents, 1996–2017.

The frequency and severity graph of mainline passenger derailments and collisions by major accident-cause groups was plotted (Figure 4). As seen in Figure 3, the graph is divided into four quadrants to enable comparison of the frequency and severity of the different cause groups. The train operation human factor (TOHF) cause group had above-average frequency and was the most severe in terms of

Table 3. Summary of frequency, accident rate, casualties, and average casualties for different types of passenger train accidents, 1996–2017.

Type	Frequency	Percentage (%)	Average accident rate	Total casualties	Percentage (%)	Average casualties
Grade crossing	706	49.2	0.3743	1311	27.3	1.86
Obstruction	393	27.4	0.2084	436	9.1	1.11
Derailment	261	18.2	0.1384	1765	36.7	6.76
Collision	61	4.3	0.0323	1284	26.7	21.05
Miscellaneous	14	1.0	0.0074	10	0.2	0.71
Total	1435	100.0	0.1522	4806	100.0	3.35

Table 4. List of foreign objects in obstruction incidents and frequency, 1996–2017.

Object	Frequency
Vehicle (not at grade crossings)	138
Tree	100
Unknown debris	44
Boulder/rock	33
Metal	16
Bumper	11
No description	7
Uncategorized debris	7
Crossing gate	6
Animal	5
Bridge plate	4
Concrete block	4
Fence	4
Ice/snow	3
Asphalt	2
Shopping cart	2
Utility pole	2
Bar stool	1
Cable spool	1
Gallon drum	1
Pleasure boat	1
Signal equipment	1
Total	393

average casualties, accounting for 30% of the total derailments and collisions, but 69.6% of the total casualties (Table 5). Track, roadbed, and structures (TRS) accidents were more frequent than TOHF, but less severe (40.1% of the total derailments and collisions and 25.8% of the total casualties). Both TOHF- and TRS-related accident causes consistently represented the most frequent and severe accident-cause groups, together accounting for a total of 70.2% of derailments and collisions, and 95.3% of casualties; therefore, they were analyzed in more detail.

In order to identify the trends in specific accident causes, a five-year moving average of combined derailment and collision rate was broken down by accident-cause group (Figure 5). TRS and TOHF were consistently the most frequent accident-cause groups over the 22-year study period, with TRS being the highest for every five-year interval except 1998–2002, 2008–2012, and 2012–2016. The trend implies that the distribution of accident causes for passenger train derailments and collisions has changed over the period studied and may reflect the railroad industry's emphasis on preventing certain types of accident causes. For example, prior to 2010, infrastructure-related accidents comprised a large fraction of passenger train derailments, but these have been substantially reduced since then due to investment in infrastructure and defect detection technologies. The decreasing trend of infrastructure-related accidents has led to a shift in focus toward reduction of human-factor-caused accidents.

The accident-cause groups were further analyzed by preparing a frequency and severity graph for the more detailed accident-cause subgroups (Figure 6). Each data point represents one accident-cause subgroup. Data points with the same color and shape indicate that these subgroups are in the same accident-cause group. In terms of average casualties, four accident-cause subgroups were in the upper-right quadrant, and thus most likely to pose the greatest risk due to their high frequency and severity. All of them are from the TOHF group:

- Failure to Display/Obey Signals (05H)
- Train Speed (10H)
- Miscellaneous Human Factors (12H)
- Mainline Rules (08H)

These four subgroups accounted for 20.8% of the total mainline passenger derailments and collisions but 67.5% of total casualties (Table 6). Among all the subgroups identified in the upper-right quadrant, Miscellaneous Human Factors had the highest average casualties per accident, followed by Failure to Display/Obey Signals, Train Speed, and Mainline Rules. Overall, the five most frequent accident-cause subgroups were: Turnout Defect – Switches, Failure to Obey/Display Signals, Wide Gauge,

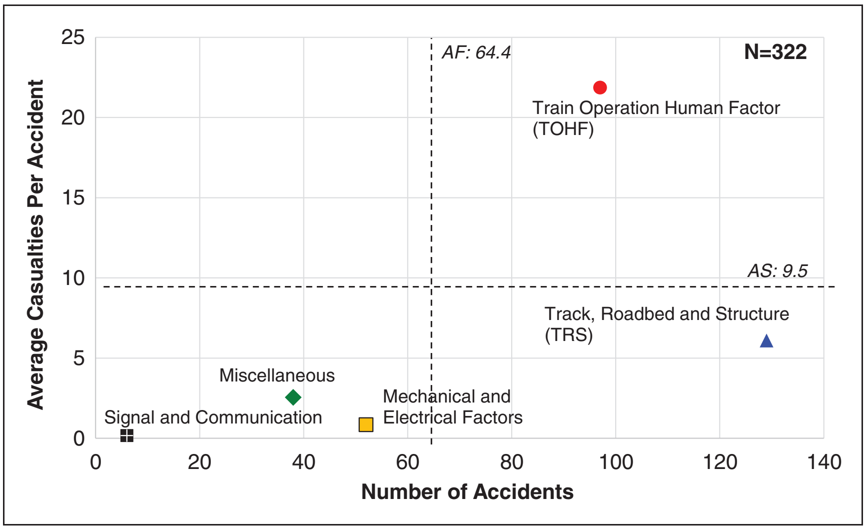

Figure 4. Frequency and severity graph of mainline passenger derailments and collisions, 1996–2017, by accident-cause group with average casualties.
AF: average frequency; AS: average severity.

Table 5. Summary of frequency, accident rate, casualties, and average casualties of mainline passenger derailments and collisions, 1996–2017, by accident-cause group.

	Frequency	Percentage (%)	Average rate	Total casualties	Percentage (%)	Average casualties
Train operation human factor (TOHF)	97	30.1	0.0514	2121	69.6	21.87
Track, roadbed, and structure (TRS)	129	40.1	0.0684	786	25.8	6.09
Miscellaneous	38	11.8	0.0201	97	3.2	2.55
Mechanical and electrical factors	52	16.1	0.0276	44	1.4	0.85
Signal and communication	6	1.9	0.0032	1	0.0	0.17
Total	322	100.0	0.1707	3049	100.0	9.47

Other Miscellaneous, and Use of Switches. Combined, they accounted for 43.5% of total derailments and collisions and 41.9% of total casualties. Two of the top five most frequent accident-cause subgroups were infrastructure related, two of them were due to human factor and one of them was miscellaneous.

The frequency and severity of each accident-cause subgroup for mainline passenger train derailments and collisions were ranked by average casualties (Table 6). Buckled Track, Infrastructure Damage Causes, and Joint Bar Defects were the top three accident-cause subgroups indicating that although they occurred infrequently, on average they had high severity when they did occur. This characteristic is also illustrated by their placement in the upper left quadrant of Figure 6. Miscellaneous Human Factors, Failure to Obey/Display Signals, Train Speed, and Mainline Rules were the fourth to seventh ranked accident-cause subgroups. They also had high average severity, but they were more frequent than the previous three accident-cause subgroups. This is also consistent with the result shown by the frequency–severity graph (Figure 6).

PTC preventable accident causes

PTC refers to an advanced train control system that is being implemented to prevent train-to-train collisions, overspeed derailments, incursion into established work zones, and derailments due to misaligned switches.[96] Among the most frequent passenger-train accident-cause subgroups are PTC-preventable accidents (PPA). For example, accidents due to Failure to Obey/Display Signals (05H), Use of Switches (11H), Mainline Rules (08H), Train Speed (10H) will often be PPAs. All four accident-cause subgroups identified in the upper-right quadrant in the frequency–severity graph are also generally PPAs. The average casualties for these PPA-cause subgroups are greater than the average severities for all accident-cause subgroups combined (Table 6).

Effect of speed on passenger train derailments and collisions

Previous research has shown that on average the speed of a train at the time of derailment was positively correlated with derailment severity.[33,35–37,40–42]

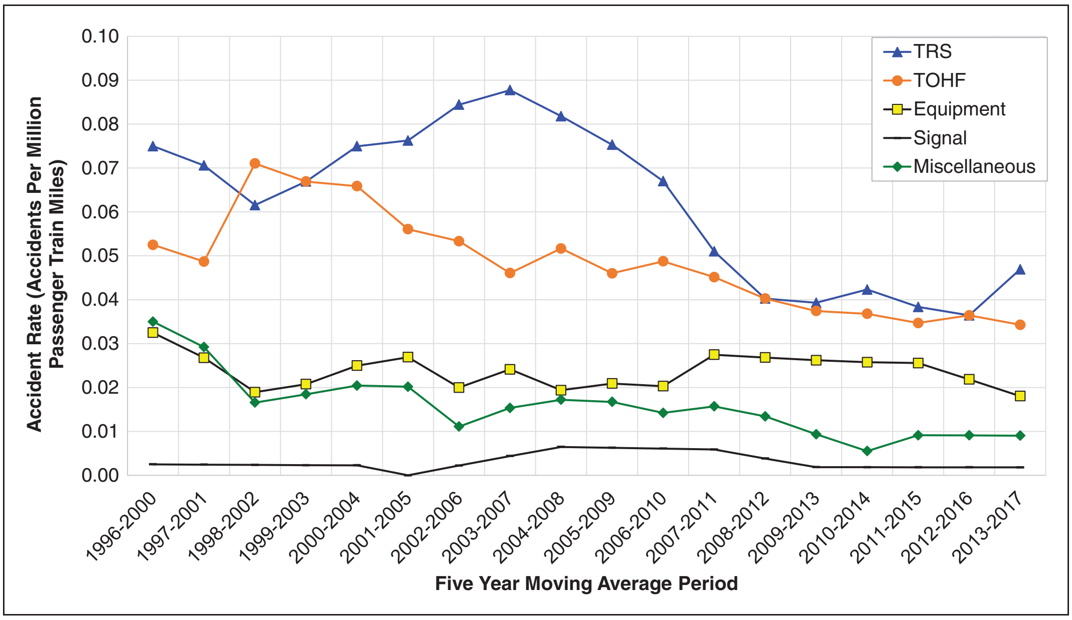

Figure 5. Five-year moving average of combined mainline passenger train derailment and collision rate, 1996–2017, by accident-cause group.
TOHF: train operation human factor; TRS: track, roadbed and structure.

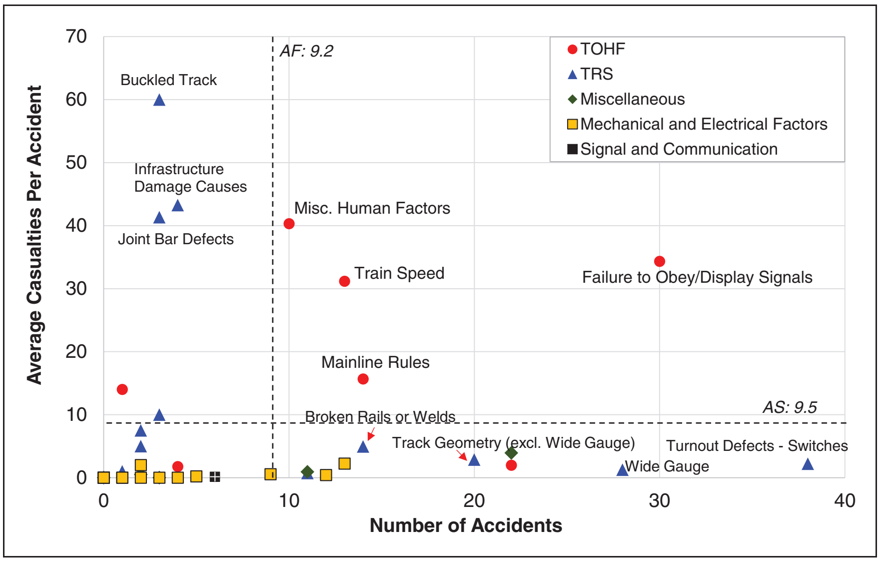

Figure 6. Frequency and severity graph of mainline passenger derailments and collisions, 1996–2017, by accident-cause subgroups with average casualties.
TOHF: train operation human factor; TRS: track, roadbed and structure.

Previous research has also found an inverse relationship between the FRA track class and the freight train derailment rate.[34,37,40,97]

The number and percentage of mainline passenger train derailments and collisions by speed range and accident-cause category were plotted (Figure 7). The majority of train accidents – about 57% – occurred at speeds below 20 mph. This may be related to the relatively high frequency of defective-turnout-caused derailments. Turnouts are found at stations, terminals, and at the ends of sidings where trains are likely to slow down due to speed restrictions, scheduled stops, or meet/pass activities. Infrastructure-related accidents occurred in almost all speed ranges and had the highest percentage except the >100 mph category. No specific trends were found for human-factor-caused and equipment-caused accidents. The three accidents that occurred above 100 mph were caused by human factors and equipment.

To further understand what caused derailments or collisions at different speeds, the number of mainline passenger train derailments and collisions by accident-cause subgroup in different speed ranges was analyzed (Table 7). In the 0–20 mph range, Turnout Defects – Switches was the top accident-cause

Table 6. Summary of frequency, accident rate, severity, and average severity of mainline passenger derailments and collisions, 1996–2017, by accident-cause subgroups with at least one occurrence.

ADL cause subgroup code	ADL cause subgroup description	Frequency		Accidents per million train miles	Casualties			Cars derailed		
		Number	Percentage (%)		Number	Percentage (%)	Average	Number	Percentage (%)	Average
05T	Buckled track	3	0.9	0.0016	180	5.9	60.0	25	2.9%	8.3
02T	Infrastructure damage causes	4	1.2	0.0021	173	5.7	43.3	21	2.4%	5.3
07T	Joint bar defects	3	0.9	0.0016	124	4.1	41.3	22	2.5%	7.3
12H	Miscellaneous human factors	10	3.1	0.0053	403	13.2	40.3	35	4.0%	3.5
05H	Failure to obey/display signals	30	9.3	0.0159	1030	33.8	34.3	101	11.6%	3.4
10H	Train speed	13	4.0	0.0069	405	13.3	31.2	46	5.3%	3.5
08H	Mainline rules	14	4.3	0.0074	219	7.2	15.6	21	2.4%	1.5
04H	Employee physical condition	1	0.3	0.0005	14	0.5	14.0	18	2.1%	18.0
06T	Rail defects at bolted joint	3	0.9	0.0016	30	1.0	10.0	20	2.3%	6.7
01T	Roadbed defects	2	0.6	0.0011	15	0.5	7.5	8	0.9%	4.0
09T	Other rail and joint defects	2	0.6	0.0011	10	0.3	5.0	4	0.5%	2.0
08T	Broken rails or welds	14	4.3	0.0074	69	2.3	4.9	59	6.8%	4.2
05M	Other miscellaneous	22	6.8	0.0117	86	2.8	3.9	75	8.6%	3.4
04T	Track geometry (excl. wide gauge)	20	6.2	0.0106	57	1.9	2.9	47	5.4%	2.4
15E	Loco trucks/bearings/wheels	13	4.0	0.0069	29	1.0	2.2	18	2.1%	1.4
10T	Turnout defects – Switches	38	11.8	0.0201	84	2.8	2.2	75	8.6%	2.0
09E	Sidebearing, suspension defects (car)	2	0.6	0.0011	4	0.1	2.0	5	0.6%	2.5
11H	Use of switches	22	6.8	0.0117	43	1.4	2.0	36	4.1%	1.6
02H	Handbrake operations	4	1.2	0.0021	7	0.2	1.8	14	1.6%	3.5
03T	Wide gauge	28	8.7	0.0148	35	1.1	1.3	86	9.8%	3.1
11T	Turnout defects – Frogs	1	0.3	0.0005	1	0.0	1.0	5	0.6%	5.0
01M	Obstructions	11	3.4	0.0058	10	0.3	0.9	41	4.7%	3.7
12T	Miscellaneous track and structure defects	11	3.4	0.0058	8	0.3	0.7	23	2.6%	2.1
18E	All other car defects	9	2.8	0.0048	5	0.2	0.6	10	1.1%	1.1
04M	Track–train interaction	2	0.6	0.0011	1	0.0	0.5	5	0.6%	2.5
13E	Other wheel defects (car)	12	3.7	0.0064	5	0.2	0.4	17	1.9%	1.4
06E	Centerplate/carbody defects (car)	5	1.6	0.0027	1	0.0	0.2	2	0.2%	0.4
01S	Signal failures	6	1.9	0.0032	1	0.0	0.2	9	1.0%	1.5
11E	Other axle/journal defects (car)	4	1.2	0.0021	0	0.0	0.0	10	1.1%	2.5
17E	All other locomotive defects	3	0.9	0.0016	0	0.0	0.0	5	0.6%	1.7
07H	Switching rules	3	0.9	0.0016	0	0.0	0.0	3	0.3%	1.0
03M	Lading problems	3	0.9	0.0016	0	0.0	0.0	0	0.0%	0.0
14E	TOFC/COFC defects	2	0.6	0.0011	0	0.0	0.0	6	0.7%	3.0
07E	Coupler defects (car)	1	0.3	0.0005	0	0.0	0.0	1	0.1%	1.0
19E	Stiff truck (car)	1	0.3	0.0005	0	0.0	0.0	1	0.1%	1.0
	Total	322	100.0	0.029	3049	100.0	9.5	874	100.0%	2.7

ADL: Arthur D. Little.

subgroup, consistent with the previous suggestion regarding low-speed accident causes. In the 21–40 mph and 41–60 mph ranges, Failure to Obey/Display Signals was the most frequent subgroup. In the 61–80 mph and 81–100 mph ranges, some equipment-related accident-cause subgroups, namely All Other Car Defects and Other Wheel Defects (Car) were the top causes. The three accidents in which speed was above 100 mph were in the following three subgroups: All Other Locomotive Defects, Centerplate/Carbody Defect (Car), and Miscellaneous Human Factors. Two of these were raking collisions, and the third one was an overspeed derailment. Summaries of these three accidents are as follows (in order of the accident date):

1. 12 April 2001. Amtrak train was side-swiped by an improperly secured locomotive door from a freight train on the adjacent track (accident type: raking collision; Amtrak train speed: 110 mph, no

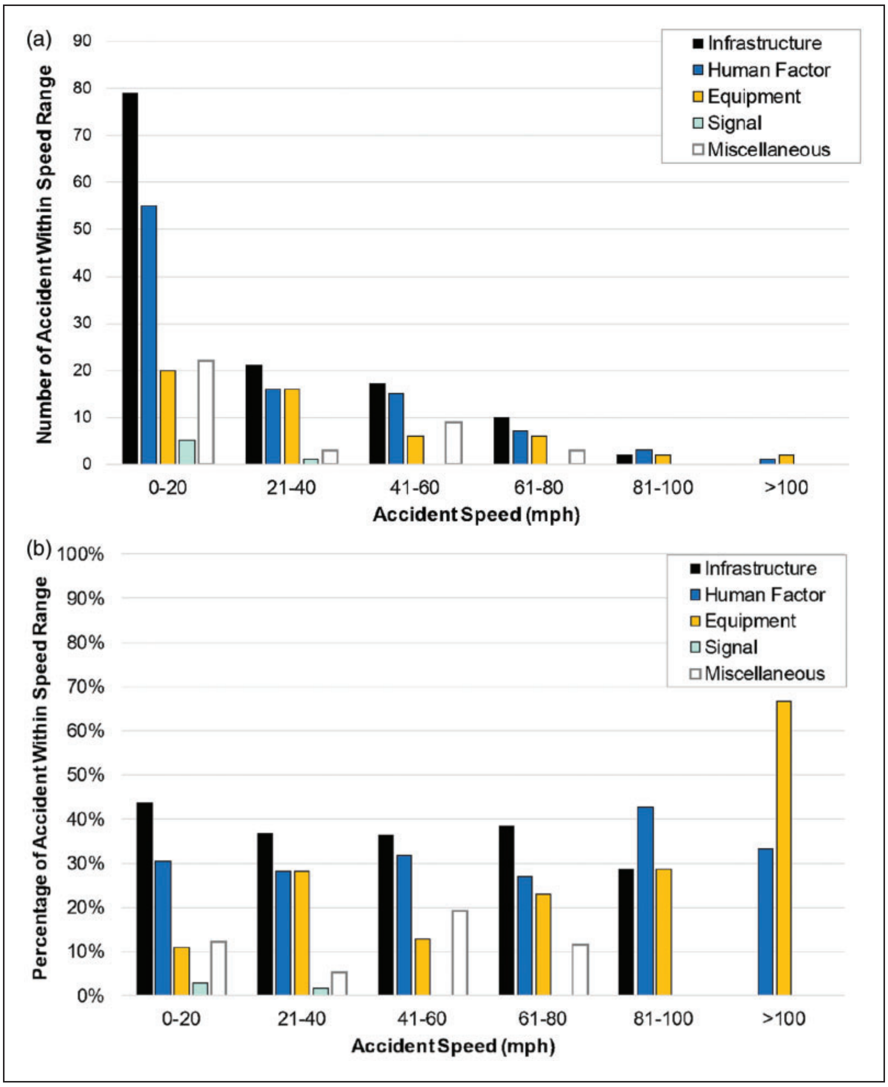

Figure 7. Number (a) and percentage (b) of mainline passenger train derailments and collisions by speed range and accident-cause category, 1996–2017.

cars derailed; no casualties; accident-cause subgroup: All Other Locomotive Defects).

2. 24 January 2004. Amtrak train was side-swiped by an improperly secured freight car door from a freight train on the adjacent track (accident type: raking collision; Amtrak train speed: 110 mph, no cars derailed, no casualties, accident-cause subgroup: Centerplate/Carbody Defect (Car)).
3. 12 May 2015. Amtrak train derailed while traveling at 102 mph in a curve with a 50-mph civil speed restriction, resulting in the derailment of one locomotive and seven passenger cars; 229 casualties; accident-cause subgroup: Miscellaneous Human Factors.[98]

Discussion

Passenger train accident data in the 22-year period from 1996 to 2017 were analyzed and major accident types and causes identified. The relationship between train speed and accident frequency, severity and accident causes was investigated. These findings provide understanding of factors affecting passenger train accident risk and a basis for further improvement in passenger train safety. Based on these results, several directions for future research are discussed.

Adjacent track accidents on shared-use rail corridors

With the development of high-speed rail, as well as continued improvement in the conventional passenger rail system in the United States, there will be more SRCs and consequently more frequent mixed passenger and freight train operations.[99] In such an environment, the consequences of train derailments and collisions have important implications for passenger safety. Of particular interest are adjacent track accidents (ATAs).[29] ATAs occur when a train derails and intrudes onto adjacent tracks, and then strikes or is struck by, trains on those tracks. With more trains

Table 7. Most frequent accident-cause subgroups of mainline passenger train derailments and collisions, 1996–2017, by accident speed ranges.

	Ranking by frequency	Accident speed range (mph)					
		0–20	21–40	41–60	61–80	81–100	>100
Top accident-cause subgroups	1	Turnout Defects – Switches	Failure to Obey/ Display Signals	Failure to Obey/ Display Signals	All Other Car Defects	Other Wheel Defects (Car)	Miscellaneous Human Factors
	2	Failure to Obey/ Display Signals	Loco Trucks/ Bearings/Wheels	Broken Rails or Welds	Joint Bar Defects	Track Geometry (excl. Wide Gauge)	All Other Locomotive Defects
	3	Use of Switches	Wide Gauge	Wide Gauge	Broken Rails or Welds	Train Speed	Centerplate/Carbody Defects (Car)
	4	Wide Gauge	Turnout Defects – Switches	Other Miscellaneous	Misc. Human Factors	Handbrake Operations	
	5	Other Miscellaneous	Mainline Rules	Obstructions	Track Geometry (excl. Wide Gauge)	Non-Traffic, Weather Causes	
	Number of Accidents	182	57	47	26	7	3

operating on a corridor, the probability of train interactions also increases, meaning that if a train derails and intrudes onto an adjacent track, there is a greater chance that another train will be present or approaching on the adjacent track.[100] Furthermore, higher passenger train speed on these SRCs means the potential consequences of an accident are also greater. Focusing on the risk of adjacent track accidents will help improve our understanding of this risk and lead to more effective risk reduction strategies.

ATAs are likely to increase in relative frequency in the coming decade due to the expected decline in frequency of PPAs, as PTC is fully implemented. Most of the accident-cause groups occupying the upper-right quadrant in Figure 6 are PPAs, whereas ATAs will not be substantially affected by PTC, leaving them as a relatively more important source of risk on SRCs, especially in multiple track territories.

Comparison of passenger train derailment/collision and freight train derailment/collision

Another important aspect of the safety of SRC is being able to more accurately estimate the train accident rates. Due to different train characteristics, infrastructure, rolling stock designs, and operating practices, the train accident rates and predominant accident causes likely differ between passenger and freight rail systems. From the analysis presented in this paper some differences in general trends in accident rates were observed. Further study of the differences in passenger and freight train derailment and collision rates, as well as the distribution of accident causes will inform more effective risk management and mitigation strategies. This is particularly important for quantifying and managing the risk on SRCs. This can be achieved by combining the statistical findings from this study with previously developed freight train derailment and collision statistics.

PTC

Our analysis indicates that PPA causes account for a large proportion of passenger train derailment and collision risk in terms of both frequency and severity. These results suggest that reducing the number of accidents due to PPA-cause subgroups will reduce the overall risk of passenger train derailments and collisions. Current railroad industry implementation of PTC is expected to substantially reduce the occurrence of many of these accidents.[101] PTC is therefore a crucial element in SRC implementation. Consequently, further research on the specific types and circumstances of accidents that PTC is intended to prevent may enable further refinement of its capabilities and those circumstances where other approaches to improving train safety will be more effective.

Human factor analysis

TOHF was identified as the most frequent and severe passenger train accident-cause category. Consequently, addressing these causes will be critical to the success of further passenger train risk reduction efforts. As mentioned in the previous subsection, several human-factor causes can be reduced or prevented by implementing PTC, including Failure to Obey/Display Signal and Train Speed Violation.

Certain human factor causes, while not the major source of risk that PTC is intended to prevent, are also important for railroad operational safety and thus require risk assessment. As discussed previously, because of constraints in the FRA data, the causal analyses principally account for the direct causes of passenger train accidents. Nevertheless, there may often be underlying factors that indirectly contribute to the occurrence of these accidents. Some examples include employee fatigue, maintenance error, workload, and organizational safety management and culture. Although these factors are not the direct, proximate cause of an accident, they can affect a wide range of railroad operations and therefore be substantial contributors to risk. Such factors may be the root or common cause, for a number of direct accident causes. Therefore, it is also suggested that the current accident cause reporting mechanics need to be changed to address this ambiguity.

Railroad human factors research encompasses a range of topics including human fatigue in train operation, ergonomics, and human performance in the train control system. Overall, there are important opportunities to reduce passenger train derailments and collision risk by addressing human factors.

Conclusion

This paper presented the results of a study to identify the most important factors contributing to the risk of passenger train accidents. Derailments and collisions were identified as the most significant passenger train accident types, and track failures and human factors, respectively, were the primary causes of those accidents. Accident causes related to human factors and train operations such as train speed violations and failure to obey signals are often high-consequence accidents and therefore pose the greatest risk. Higher risk infrastructure-related factors include track geometry defects and broken rails or welds. PPAs also account for a large portion in terms of both frequency and severity. This analysis of train accident causes is important for the rational allocation of resources to reduce accident occurrence and consequences and provides a foundation for further improvement in the passenger train safety. The paper also suggests opportunities for future research including adjacent track accident risk assessment on shared-use rail corridors, comparison of passenger and freight train accident analysis, PTC, and human factor analyses.

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