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ABSTRACT

An understanding of accident risk based on historical safety data can support the development and prioritization of effective accident prevention strategies. While previous studies have focused extensively on the safety risks associated with high-frequency-high-consequence accidents, comparatively little work has been undertaken to evaluate railroad risk and safety under restricted-speed operations. In the United States, restricted speed is defined as a speed that permits stopping within one-half the range of vision, but not exceeding 20 miles per hour. Human-reliant restricted-speed operation has been common on U.S. freight railroads for over a century. Recently, a series of severe accidents due to violations of restricted speed rules has triggered renewed interest in understanding and improving restricted-speed operational safety. To this end, this paper develops a statistical analysis of restricted-speed train accidents occurring between 2000 and 2016, based on data from the U.S. Federal Railroad Administration. Our study quantitatively analyzes the distribution of restricted-speed accident frequency, severity, risk, and other pertinent characteristics. The research finds that while the overall train accident rate has declined substantially, there is no significant improvement regarding the restricted-speed train accident rate over the studied period. In order to characterize the risk profile of this type of accident, two alternative risk measures, namely mean value and Conditional Value at Risk (CVaR), are developed to estimate an annual restricted-speed train accident risk. In particular, the CVaR represents the expected consequence in worst-case scenarios, which more effectively characterizes the low-probability-high-consequence restricted-speed accidents under certain circumstances. Furthermore, based on a micro-level study employing developed Fault Tree Analysis, effective human-error mitigation actions (e.g. valid medical program, alerter system) and advanced train control (e.g. Positive Train Control) are discussed as two primary restricted-speed accident risk prevention strategies to improve the safety level of train operations at restricted speeds.

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Train accident; risk analysis; railroad; safety

1. Introduction

Railroads play a key role in the transportation infrastructure and economic development of the United States, and safety is of the utmost importance. In the United States, train accident analysis has primarily focused on derailment, hazardous material releases, and highway-rail

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grade-crossing accidents (Anderson and Barkan 2004; Liu, Barkan, and Saat 2011; Chadwick, Zhou, and Saat 2014; Liu 2016a, 2017). However, much less research has evaluated train risk and safety for restricted-speed train accidents, in spite of the fact that restricted-speed violation is one of the most common types of operating rule compliance problems on U.S. railroads and can cause potentially high consequences under certain scenarios.

As defined in 49 Code of Federal Regulations (CFR) 236 Subpart G, restricted speed is 'a speed that permits stopping within one-half the range of vision, but not exceeding 20 miles per hour'. The regulation demands that in restricted-speed train operations, both the upper speed limit (e.g. 20 mph) and stopping within one-half the range of vision must be satisfied simultaneously. In the United States, restricted-speed operation is a common type of train operation, which is on virtually every mile of the Automatic Block Signal (ABS) and extensively employed within terminals and yards. However, relying on train engineers to make operational decisions also introduces human-error-caused risk. Operators violating restricted-speed operating rules (e.g. falling asleep, fatigue), as one common human error, has resulted in a series of recent accidents. For example, the National Transportation Safety Board (NTSB) issued a report in 2012 highlighting five rear-end collisions due to violations of restricted speeds (NTSB 2012). In all five collisions, crewmembers had failed to operate their trains at the required restricted speed.

Despite this ubiquitous risk, the prior research analyzing restricted-speed train accidents in the United States is quite limited. This knowledge gap has motivated the development of this paper, which aims to study restricted-speed train accidents that are due to human factors in the United States, with a focus on two aspects: (1) macro-level analysis of nationwide restricted-speed accident risk in the United States and (2) micro-level Fault Tree Analysis of individual accidents. Based on prior studies in accident risks (Nuclear Regulatory Commission 1990; Renn 1998; Aven and Renn 2009; Liu 2016a), the risk of restricted-speed accidents in this paper is defined as the combination of expected accident frequency and expected accident severity. For example, the annual restricted-speed accident risk could be modeled as the product of the annual expected number of restricted-speed accidents and the expected accident consequences per accident. The risk analysis method and information garnered from it can potentially provide new insights into railroad safety and risk management related to restricted-speed operations. In addition to use the expected consequence (mean value) to represent the risk, this paper also develops alternative risk measures (specifically the Conditional Value at Risk), to characterize low-probability-high-consequence restricted-speed train accidents under certain circumstances. Furthermore, our risk methodology can be adapted to other accident types or consequence metrics. Apart from a macro-level analysis of nationwide restricted-speed accidents, Fault Tree Analysis is also developed based upon specific accidents in order to explore the characteristics of individual accident cases. This developed micro-level analysis can contribute to identifying contributing factors.

2. Relevant prior literature

2.1. Railroad safety and risk studies

Rail risk analysis and accident prevention have long been a high priority for the railroad industry. Numerous prior studies have concentrated on train risk analysis associated with train derailment (Barkan, Tyler Dick, and Anderson 2003; Bagheri et al. 2011) or highway-rail grade-crossing accidents (Austin and Carson 2002; Chadwick, Zhou, and Saat 2014), and some work has been undertaken to evaluate train collision risk (Liu 2016a)—these three types of incidents comprise the three leading accident categories on U.S. railroads. In addition, extensive studies (Baysari et al. 2009; Ahmad et al. 2013; Lin et al. 2014) were also conducted to identify the contributing factors and causes in the occurrence of train accidents, including track, rolling stock, signal, human factor, as well as other miscellaneous factors (e.g. environmental conditions). Although considerable prior studies have covered diverse types of train accidents, there is still a lack of research on other specific types of train accidents, such as the ones which occur under restricted-speed operations. Restricted-speed train accidents are one common type of human-error-related accident, in which crewmembers' behavior fails to comply with restricted-speed rules. To the authors' knowledge, comparatively very little work has been conducted to analyze restricted-speed operation and its associated accident risk.

2.2. Restricted-speed train accidents

As previously stated, restricted speed is defined as a speed that will permit stopping within one-half the range of vision, but not exceeding 20 miles per hour (FRA 2011a). Besides the federal regulations, railroad operating rules also set forth definitions of movements at restricted speeds. At present, most Class I railroads (a group of the largest railroads operating in the United States, with each railroad's annual operating revenue over $433 million) use one of two 'standard' rulebooks: the Northeast Operating Rules Advisory Committee (NORAC) rulebook, and the General Code of Operating Rules (GCOR). In these two guides, GCOR (2010) has almost the same definition of restricted speed as 49 CFR 236 Subpart G, while NORAC (2018) provides a stricter requirement in interlocking. More specifically, restricted speeds in NORAC are required to not exceed 20 mph outside interlocking limits or 15 mph within interlocking limits.

However, railroad restricted speed is not a simple numerical value. Train movement must be made at a speed that allows for stopping within half the range of vision short of a variety of hazards, such as other trains, engines, railroad cars, stop signals, men or equipment fouling the track, as well as obstructions (GCOR 2010; NORAC 2018). In 1999, Coplen (1999) pointed out that the violation of restricted-speed rules was one of the most common types of rule compliance problems on U.S. railroads. Several rear-end train collisions occurring in 2011 and 2012, in which crewmembers failed to operate their trains under the required restricted speeds, were discussed by NTSB (2012) and the U.S. Federal Railroad Administration (FRA 2012). One of them, a rear-end collision of two BNSF Railway (BNSF) trains in 2011, led to two fatalities and more than $8 million in estimated damage costs. The probable cause was the failure of the crew to comply with the signal indication and to stop short of the train because they had fallen asleep (NTSB 2012). More recently, one end-of-track collision at Hoboken Terminal in New Jersey, 29 September 2016, occurred at restricted speeds and has provoked concerns from the public and rail industry. It led to one fatality, 110 injuries, and around $6 million in damage costs to the train, track, and facility. One probable cause behind this severe accident was the failure of this train's engineer to stop the train after entering Hoboken Terminal with excessive speed (NTSB 2018a).

Apart from human errors that can contribute to the occurrence of restricted-speed accidents, environmental conditions and terrain along the railway are also contributing factors in some accidents. More specifically, the range of vision, as one key part in the definition of restricted speed, varies with some key physical features in advance of the train, such as a descending grade or a reduced visibility due to severe weather conditions. In some cases, the sensitive range of vision can result in trains not being stopped short of an obstruction or a switch not being properly lined, leading to an accident.

2.3. Knowledge gap

Although there is increasing concern with restricted-speed operations and accidents, to our knowledge, there has been very limited analysis of restricted-speed train accident risk in the United States in the prior literature. This knowledge gap has motivated the development of this study, in which restricted-speed accident data are statistically analyzed for quantitative risk analysis. Due to the complexity of this subject and the content limit of this paper, this paper focuses on restricted-speed train accidents that are due to crewmembers' failure to comply with restricted-speed rules, instead of all other causes (e.g. track, mechanical, signaling, and other human errors), in the United States.

3. Data

3.1. Data sources

The accident data employed in this study come from the FRA's Rail Equipment Accident (REA) database. The FRA, part of the U.S. Department of Transportation (U.S. DOT), publishes train accident data based on reports submitted by railroads operating in the United States. Railroads are required to submit accident reports for all accidents that exceed a specific monetary threshold for damage and loss. The reporting threshold for the REA is periodically adjusted for inflation and increased from $6600 in 2001 to $10,500 in 2016 (FRA 2017a). The REA database records comprehensive circumstances regarding the accidents under over 50 different fields, including operational factors, environmental factors, train characteristics, damage conditions, and other information necessary for accident analysis and prevention. This study uses accident data for all types of accidents associated with the violation of restricted speeds from 2000 to 2016.

In addition to railroad accident datasets, traffic volume is used to calculate derailment rate, which is defined as the number of derailments normalized by traffic volume (Anderson and Barkan 2004; Evans 2011; Liu 2017). Train-miles and car-miles are two common traffic metrics, each of which corresponds to certain types of accident causes. Schafer and Barkan (2008) found that some accident causes are more related to train-miles, including most human-error failures. On the other hand, the causes of most equipment failure and infrastructure failure are more closely related to car-miles. One publicly accessible traffic volume data source is the FRA Operational Safety Database. This database records the monthly train-mile data that will be employed in the following accident analysis.

3.2. Data collection

A restricted-speed accident dataset was developed based upon the FRA's REA database and involves all types of trains and all types of track in this study. Accident narratives and causes are employed as the criteria to identify restricted-speed accidents. Narrative is a field in which a short text description of the accident was provided by the railroad correspondent. In these accidents' narratives, keywords such as 'restricted speed' or 'restricting signal' are adopted to collect restricted-speed accidents. In terms of accident causes, they were compiled into two fields of FRA's REA database, namely CAUSE and CAUSE2. CAUSE is defined as the primary cause of an accident and CAUSE2 is a contributing cause of the accident. Both CAUSE and CAUSE2 use a cause code (a coded variable with 389 values) in each field. Either of them having a restricted-speed-related cause code would mostly indicate a restricted-speed accident. Per railroad expert judgments, three cause codes, H603, H605, and H607, have a straightforward relationship with restricted-speed accidents due to human error (FRA 2017b) and are used in our data collection. The descriptions of them are as shown in Table 1. The definitions of yard limits and interlocking

Table 1. U.S. FRA accident cause codes related to accidents at restricted speeds (FRA 2011a).

Cause code	Description
H603	Train on main track inside yard limits, excessive speed.
H605	Failure to comply with restricted speed in connection with the restrictive indication of a block or interlocking signal.
H607	Failure to comply with restricted speed or its equivalent not in connection with a block or interlocking signal.

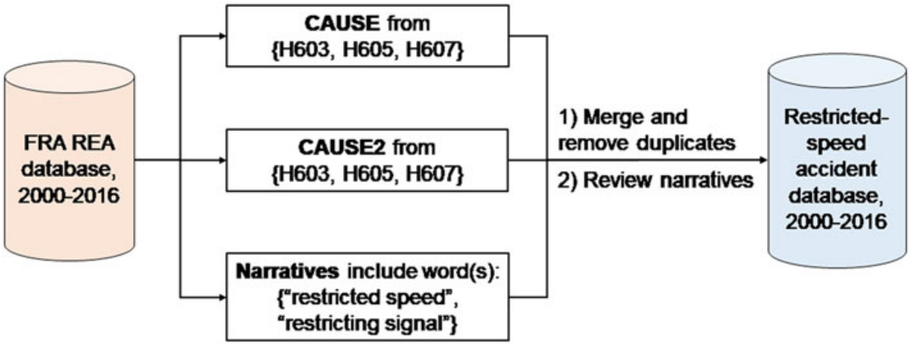

Figure 1. Restricted-speed accident collections.

are stated in the Operating Rules (GCOR 2010; NORAC 2018) and Federal Regulations (49 CFR Part 236.750) (FRA 2011a). Yard limits are the main track area between yard limit signs and designated in the Timetable or special instructions. The leading end of movement within yard limits must operate under restricted speeds. Interlocking is an arrangement of signals that are interconnected by means of electric circuits, so that train movements over all routes are governed by signal indications succeeding each other in the proper sequence.

In addition, we manually reviewed the accident narratives to verify that the included accidents were indeed due to violation of restricted-speed operating rules (e.g. operating the train above 20 mph in the restricted-speed territory). A general flowchart for restricted-speed accident data collection is presented in Figure 1. In the restricted-speed accident dataset, 887 restricted-speed train accidents were identified and collected from 2000 to 2016 for the following empirical and statistical risk analysis. These 887 restricted-speed accidents include both freight-train accidents and passenger-train accidents on all types of tracks (e.g. main, yard, siding, and industry). Selected high-consequence restricted-speed accidents are listed in Appendix.

4. Analysis of accidents under restricted speeds

Based on the FRA data from 2000 to 2016, on average, there were 52 restricted-speed accidents per year in the United States. In the 17-year study period, those restricted-speed accidents have led to 10 fatalities and 512 injuries. If the reportable damage cost (damages to track infrastructure, equipment, and signals) is adjusted to 2016 dollars using the GDP deflator (World Bank 2017) with the consideration of inflation, the total cost of damage is around $146 million (at the 2016 dollar-value) in this period. Most of those restricted-speed accidents occurred in the form of either derailments or collisions, each accounting for 39%, respectively. Other accident types, such as obstruction by objects on the track (e.g. bumper blocks, standing track inspector, standing ballast regulator), accounted for 22% of restricted-speed train accidents. The statistical analysis of accident frequency, severity, and risk (measured by casualty or damage cost) will be discussed in following subsections (Figure 2).

4.1. Restricted-speed accident rate

Figure 3 compares the empirical accident rate (number of train accidents normalized by traffic exposure such as train-miles) for restricted-speed train accidents with two other leading accident causes on U.S. freight railroads: broken rails and track-geometry failures. While broken rails were the leading accident cause in the United States for the last 17 years, the rate for this cause has declined steeply, dropping by around 50%. A significant safety improvement has

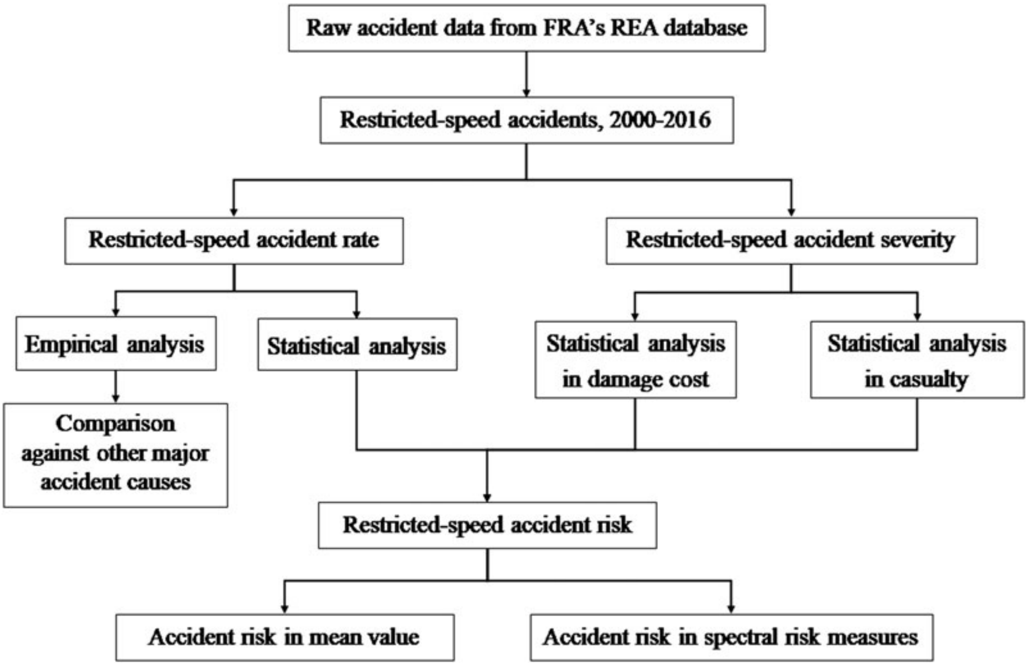

Figure 2. Flowchart of the methodology implemented.

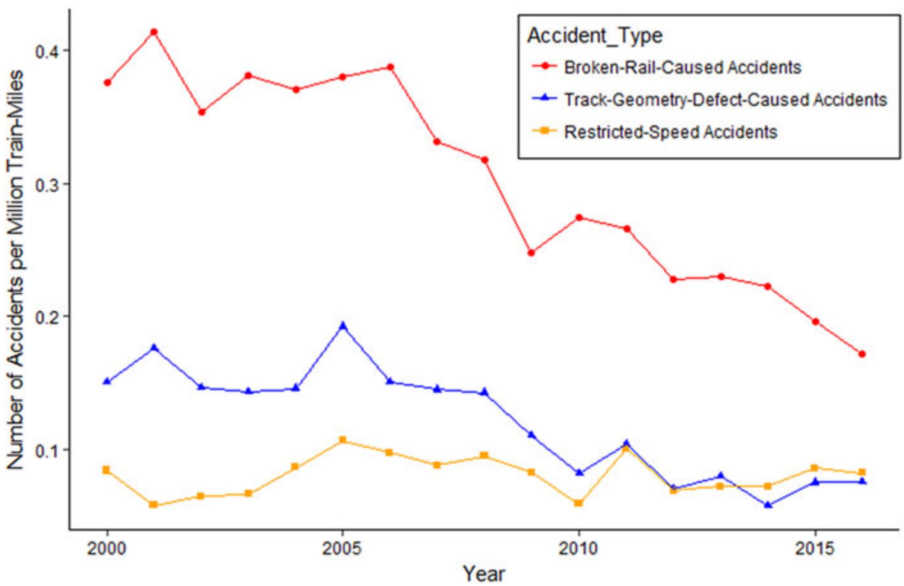

Figure 3. Temporal trend in accident rates for three accident groups in the United States. 2000–2016.

also been observed for track-geometry-failure-caused accidents. The reduction in the rate of infrastructure-caused accidents is not surprising. Over the past two decades, the U.S. railroad industry has invested extensively in advanced track detection technologies and risk-based maintenance strategies to increase infrastructure quality (Barkan, Tyler Dick, and Anderson 2003; Saadat et al. 2014; Peng and Ouyang 2014). The graph shows no apparent indication that the rate of restricted-speed accidents has been either increasing or decreasing over the last 17 years.

As a result of this dissimilar temporal trend, the rate of restricted-speed accidents has actually surpassed that of track-geometry-defect-caused accidents since 2013.

A statistical model can be developed to estimate the restricted-speed train accident rate. Based on a prior study, this study accounts for two potential contributing factors, the year and annual traffic exposure (Liu 2017). The year variable represents the temporal change in the frequency of restricted-speed train accidents given certain traffic exposure. The annual traffic exposure variable tests whether and how the count of restricted-speed accidents varies with traffic volume in a given year. First, a Negative Binomial (NB) regression model is applied. As a generalization of Poisson regression, the NB model is for modeling count variables and also relaxes the assumption that the variance is equal to the mean made by the Poisson model. The NB model has been extensively applied to accident rate analysis for both highway transportation (Lord 2006; Mitra and Washington 2007) and railway transportation (Oh, Washington, and Nam 2006; Liu, Saat, and Barkan 2017) and showed promising results with an acceptable goodness-of-fit. Therefore, this article employs it to model the number of restricted-speed accidents in the United States. Specifically, as shown in Equations (1) and (2), the observed number of accidents (Y) is assumed to follow a Poisson distribution, in which the coefficient, λ, is assumed to follow a Gamma distribution. Thus, the NB model is also called the Poisson-Gamma mixture model (Hosmer, Lemeshow, and Sturdivant 2013). From this, the estimated number of accidents can be formulated as $\exp\left(\sum_{p=0}^{k} b_p X_p\right) M$. The basic framework is as follows (Liu, Saat, and Barkan 2017): the model output is the number of accidents given traffic exposure, and the predictor variables are influencing factors that affect the accident rate.

$$Y \sim Poisson(\lambda) \tag{1}$$

$$\lambda \sim Gamma\left(f, \frac{f}{m}\right) \tag{2}$$

$$m = \exp\left(\sum_{p=0}^{k} b_p X_p\right) M \tag{3}$$

where Y = observed number of restricted-speed accidents, m = estimated number of restricted-speed accidents, $b_p = p^{\text{th}}$ parameter coefficient, $X_p = p^{\text{th}}$ explanatory variable, M = traffic exposure (e.g. train-miles), and f = inverse dispersion parameter.

In the study of restricted-speed accidents, it is assumed that accidents occur stochastically across the total traffic for a specific year with a NB distribution, with a mean count per year (y_i) as a function of year index and traffic volume:

$$y_i = \exp(\alpha + \beta \times T_i + \gamma \times M_i) M_i \tag{4}$$

where y_i = expected number of restricted-speed accidents in year i, T_i = year index, M_i = million train-miles in year i, and $\alpha,\ \beta, \gamma$ = parameter coefficients.

Three parameter coefficients, α, β, and γ, are estimated using the method of maximum likelihood (Hosmer, Lemeshow, and Sturdivant 2013). The model (4) has been fitted to the 2000–2016 restricted-speed accidents to estimate these three unknown parameter coefficients. The p value of a parameter estimator represents the statistical significance of a predictor variable using the Wald test (Hilbe 2007). A generally acceptable rule is that if a predictor variable has a p value smaller than 5%, this variable is statistically significant. This model tests whether the restricted-speed accident rate changes with time. If the p value of the index year is smaller than 0.05 and the coefficient is positive, it indicates that accident rate increases with time (indicating diminishing safety). Otherwise, the accident rate reduces over time. If the p value is greater than 0.05, it illustrates that there is no statistical significant trend in the accident rate during the study period. The analysis shows that there is an insignificant temporal change in the train accident rate under restricted speeds ($p > 0.05$). On the contrary, the parameter coefficient for the variable

Table 2. Parameter estimates of accident frequency under restricted speeds, 2000–2016.

Parameter	Estimate	Standard error	Wald chi-square	p value
α	−4.067	0.656	−6.251	<0.001
γ	0.003	0.001	2.420	0.016

traffic exposure is significantly positive ($\gamma = 0.003$, $p < 0.05$). This value illustrates that traffic exposure has a significant effect on the restricted-speed accident rate. A larger traffic volume is associated with a higher accident frequency. Using variables selections and updated modeling, a 'final' model is $y_i = \exp(-4.067 + 0.003 \times M_i)M_i$. Table 2 shows the regression results and the last column is the p value of a parameter estimator.

A Pearson's test (Agresti and Kateri 2011) is developed to evaluate the goodness-of-fit of the regression model. The test shows that the p value is greater than 0.05 (p value = 0.1432, degree of freedom = 16). Thus, the developed model adequately fits the empirical data in this study. The analysis shows that there is a non-linear relationship between the restricted-speed accident rate (y_i/M_i) and traffic volume (train-miles, M_i) (Equation (5)). When traffic exposure increases, the restricted-speed accident rate per train-mile also increases, probably due to the increased opportunities for train encounters (Nayak, Rosenfield, and Hagopian 1983).

$$\frac{\partial\left({}^{y_i}/_{M_i}\right)}{\partial(M_i)} = \frac{\partial(\exp(-16.380 + 0.003M_i)}{\partial(M_i)} = 0.003 \times \exp(-16.380 + 0.003M_i) > 0 \qquad (5)$$

A sensitivity analysis is conducted here to estimate the restricted-speed accident rate given different traffic levels. If there is an annual 3% decrease in baseline traffic volume (the average traffic volume for 2000–2016, i.e. 647.5 million train-miles), the number of accidents per million train-miles will decrease from 0.076 to 0.073, which comprises a 5% accident rate reduction. Inversely, an annual 3% increase in baseline traffic volume can lead to a 5% accident rate boost in restricted-speed accidents.

4.2. Restricted-speed accident severity

There are several measures of train accident severity, such as the number of casualties (Lin et al. 2014), damage costs to rolling stock and infrastructure (Liu, Saat, and Barkan 2010), and the number of cars derailed, a common metric in the studies of derailment (Barkan, Tyler Dick, and Anderson 2003; Liu, Saat, and Barkan 2012). In this study, two proxy variables are employed to measure the severity of restricted-speed accidents, which are the number of casualties and the damage costs. Other proxies for accident consequence, such as business losses and environmental impacts, vary among accidents and this information is not reported to FRA, and was therefore excluded from the analysis herein. The number of casualties is the summation of injuries and fatalities. In terms of consequences measured by reportable damage costs (damages to track infrastructure, equipment and signals), inflation is taken into consideration and the damage cost in each year is also adjusted to the 2016 dollar-value using the GDP deflator (World Bank 2017).

Table 3 shows the distribution of the severity of restricted-speed accidents measured by casualties or damage cost per accident in each year. A Wald-Wolfowitz runs test is used to check whether a dataset comes from a random process (Liu 2016a). When the p value in the test is greater than 0.05, one may conclude that there is no statistically significant temporal trend in the studied period. In the case of this particular study, the result of the runs test indicates that there is no significant temporal trend for either casualties (p value = 0.605) or damage cost (p value = 0.301). The annual fluctuation in accident severity is largely due to random variations. Therefore, the following risk analysis uses the average restricted-speed accident severities, which are 0.545 casualties per accident and around $165,000 in damages per accident.

Table 3. Restricted-speed accident severity in casualties and damage cost per accident, 2000–2017.

Year	Casualties per accident	Damage cost per accident (in 2016 $)
2000	0.943	169,925
2001	0.250	120,911
2002	0.244	85,691
2003	0.674	109,047
2004	0.914	86,093
2005	0.918	163,999
2006	0.271	157,169
2007	2.517	174,517
2008	0.524	80,146
2009	0.500	86,738
2010	0.028	99,607
2011	0.349	126,784
2012	0.182	415,308
2013	0.489	456,671
2014	0.208	187,795
2015	0.164	117,877
2016	0.082	166,087
Average	0.545	164,963
Standard error	0.142	26,241
p Value in runs test	0.605	0.301

5. Accident risk analysis

5.1. Mean value as risk measure

Several previous studies have defined risk as the combination of possible consequences and associated probabilities (Lowrance 1976; Aven and Renn 2009). In the field of railroad safety, accident risk is measured by the combination of expected accident frequency and expected accident consequences (Liu 2016a). Using this risk measure, this paper defines annual restricted-speed accident risk as the expected number of casualties or damage costs during a year in total. As shown in Equation (6), the risk is equivalent to the expected summations of either casualties or damage costs (accident severity, X_{ij}) for all restricted-speed accidents in 1 year (accident severity, N):

$$R_{1i} = E\left(\sum_{j=1}^{N} X_{ij}\right) \tag{6}$$

where $i = \begin{cases} 1, & \textit{using number of casualties as accident severity metric} \\ 2, & \textit{using damage costs as accident severity metric} \end{cases}$, R_{1i}= annual restricted-speed accident risk (mean) based on the severity metric used, N = number of restricted-speed accidents in one year, and X_{ij} = accident severity, either in casualty or damage cost.

Both accident frequency (N) and severity (X_{ij}) are random variables. Using the Law of Total Expectation (Weiss 2006), Equation (6) can be expanded as follows:

$$E\left(\sum_{j=1}^{N} X_{ij}\right) = E\left[E\left(\sum_{j=1}^{N} X_{ij} | N = n\right)\right] \tag{7}$$

Then Equation (7) can be further written as

$$E\left(\sum_{j=1}^{N} X_{ij}\right) = E\left[E\left(\sum_{j=1}^{N} X_{ij} | N = n\right)\right] = E[NE(X_{ij})] = E(N)E(X_{ij}) \tag{8}$$

According to Equation (8), the annual accident risk is numerically equal to the product of expected accident frequency and expected severity. E(N), as the expected value of accident

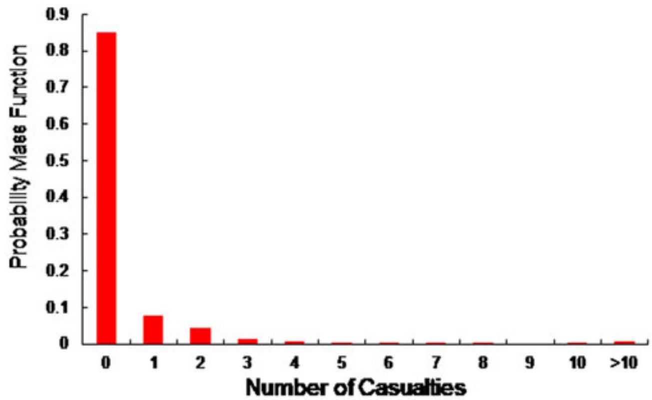

Figure 4. Distribution of average casualties per restricted-speed accident, 2000–2016.

frequency with a NB distribution, can be calculated using a developed regression model, $y_i = \exp(-4.067 + 0.003 \times M_i)M_i$, given traffic volume in each year. $\mathrm{E}(X_{ij})$, as the expected value of accident severity, is equal to the mean value of empirical accident severity, based on the insignificant temporal trend found in Section 4.2.

5.2. Alternative risk measures

One limitation of using the expected consequence (mean value) to represent the risk is that it does not fully represent the low-probability-high-consequence characteristics of train accidents. For example, about 85% of restricted-speed accidents occurred with no casualties, yet five of the restricted-speed accidents resulted in over 20 casualties (Figure 4). The mean value alone does not fully represent the potential of high-impact accidents.

To account for the 'heavy-tail' (long-tail) effect in risk analysis, alternative risk measures have been developed. They are referred to as 'spectral risk measures' (SRM), particularly Value at Risk (VaR) or Conditional Value at Risk (CVaR), which have primarily been employed in financial engineering (Soleimani, Seyyed-Esfahani, and Kannan 2014), social sciences (Cotter and Dowd 2006), highway hazardous materials transportation (Kwon 2011; Toumazis and Kwon 2016), and, recently, rail transport of hazardous materials (Hosseini and Verma 2017). These prior studies have found that VaR and CVaR are useful alternative risk measures to capture the 'worst-case-average' of accident consequences. To our knowledge, there has been no prior study applying alternative risk measures to the analysis of railroad accident risk.

The VaR is the α-quantile $\alpha \in (0,1)$ of a distribution. CVaR, also known as Expected Shortfall, is basically the weighted average of all outcomes exceeding the confidence interval of a dataset sorted from worst to best. For example, $CVaR_{0.95}$ of the number of casualties is the mean (average) of all the numbers of casualties within the worst 5% of train accidents in terms of number of casualties. Overall, VaR gives a range of potential losses and CVaR gives an average expected loss within the most severe accidents. Equations (9) and (10) give the mathematical formulas for VaR and CVaR, respectively, and α is set as 95%.

$$VaR_\alpha(X) = \min\{x : P(X \le x) \ge \alpha\} \tag{9}$$

$$CVaR_\alpha(X) = \varepsilon[x | x \ge VaR_\alpha(X)] \tag{10}$$

Previous studies stated that VaR does not account for the losses/consequences beyond the threshold amount indicated by the measure (Rockafellar and Uryasev 2000; Sarykalin, Serraino, and Uryasev 2008). It also has undesirable mathematical characteristics, such as a lack of subadditivity and convexity. In addition, VaR is difficult to optimize when it is calculated from scenarios

(Rockafellar and Uryasev 2000). As an alternative measure of risk, CVaR displays superior properties in comparison to VaR, such as being positively homogeneous, convex, and monotonic (Rockafellar and Uryasev 2000). Thus, the following analysis employs CVaR as an alternative risk measure. However, the analysis can be adapted to VaR or other SRM as well.

We consider $CVaR_{95\%}$, which represents the mean of the 5% most severe (in terms of either damage costs or casualties) restricted-speed train accidents. The annual risk is defined as follows:

$$R_{2i} = CVaR_{95\%}\left(\sum_{j=1}^{N} X_{ij}\right) \tag{11}$$

where $i = \begin{cases} 1, & \text{using number of casualties as accident severity metric} \\ 2, & \text{using damage cost as accident severity metric} \end{cases}$, R_{2i} = annual restricted-speed accident risk (spectral risk measure) based on severity metric used, N = number of restricted-speed accidents in a specific year, and X_{ij} = accident severity (e.g. casualty or damage cost).

5.3. Risk analysis results

The accident risks are summarized in Figure 5. It is not surprising that accident risks calculated according to $CVaR_{95\%}$ are always greater than mean value risks since CVaR stands for the 5% worst cases and provides insights into potentially high-severity accidents under restricted speeds. A Wald-Wolfowitz runs test was used again to test whether various accident risks follow any significant temporal trends. The statistical test results indicate that the accident risks for both two measures, R_{1i} (mean) and R_{2i} (CVaR), have no significant temporal trends in the study period.

In the period, on average, the annual restricted-speed accident risk totals 32 casualties or $8.61 million in damage costs to infrastructure and rolling stock. By contrast, on average, the worst 5% of restricted-speed accidents are expected to cause 108 casualties or $14.13 million in damage costs annually. Furthermore, the ratio of CVaR to mean value in casualties is over 3, which is larger than the ratio of CVaR to mean value in damage costs (which is around 2). This indicates that accident risk measured by casualties may have a more significant 'heavy-tail' in the worst accident consequences. This is also consistent with the empirical analysis, in which 85% of restricted-speed accidents led to zero casualties whereas some severe accidents led to dozens of casualties. The risk analysis implies that the use of alternative risk measures can provide additional insights into certain types of low-probability-high-consequence restricted-speed train accidents. Depending on the question under consideration and decision-makers' attitudes toward risk, specific risk measures can be used. Also, when potential risk mitigation strategies are evaluated and compared, using different risk measures could provide information about a specific strategy's effect on the risk profile, in terms of either overall average or worst-case scenarios.

6. Micro-level analysis of restricted-speed accidents using fault tree analysis

In addition to nationwide restricted-speed accident risk analysis in the previous sections, a micro-level analysis of restricted-speed train accidents is conducted in this section to identify the causal factors and logic paths that contribute to the restricted-speed accidents. To achieve this objective, Fault Tree Analysis (FTA) is employed to visually describe the individual restricted-speed accidents based on data from the FRA REA database and NTSB investigation reports. FTA is a deductive analytical approach in which a top event is analyzed using Boolean logic to combine a series of basic events and identify process hazards. Compared with most traditional accident causation models, FTA is easy to read and understand, with qualitative descriptions of potential problems and a combination of multiple events causing specific problems of interest.

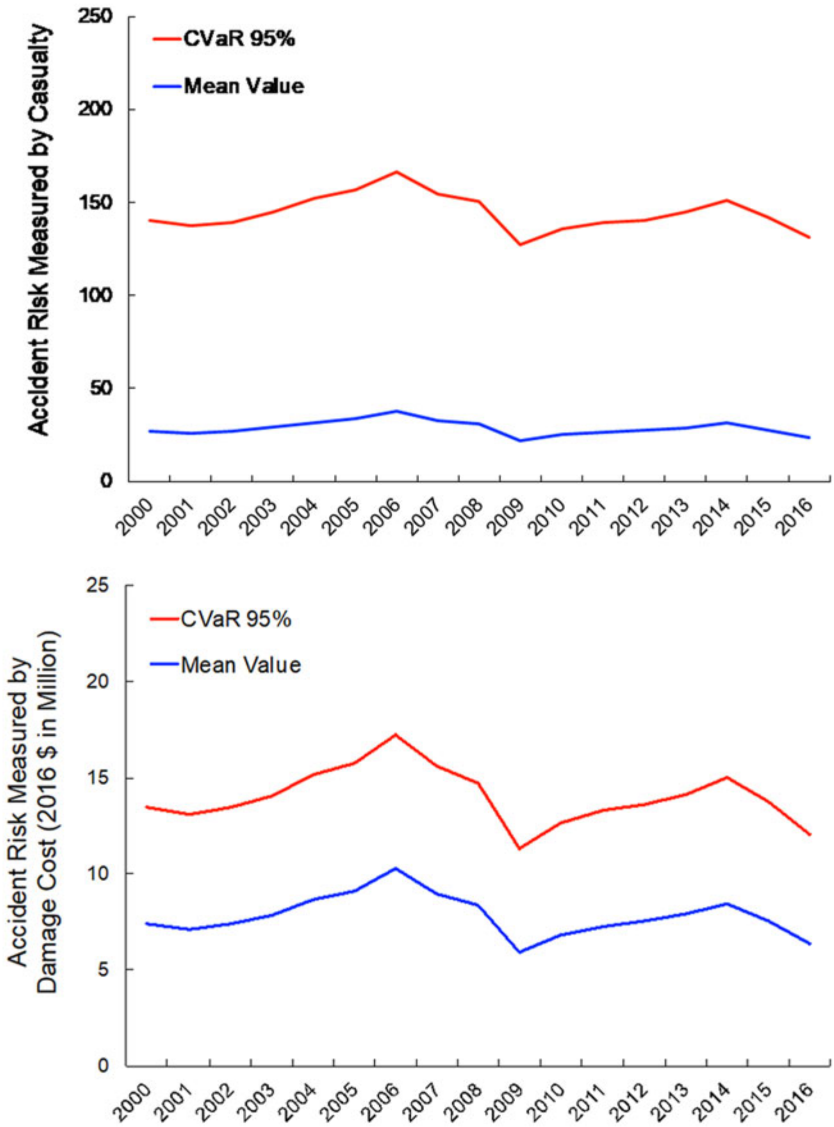

Figure 5. Annual restricted-speed accident risk in mean and CVaR, 2000–2016.

Li et al. (2013) pointed out that FTA is one of the most significant logic and probabilistic techniques used in system reliability assessment. As one common risk assessment technique, it has been widely used in a variety of previous railway risk studies. More specifically, Lin et al. (2014) studied the adjacent-track accidents by using Boolean algebra based upon the results from the FTA. Liu et al. (2015) investigated high-speed railway accidents using the FTA combined with quantitative analysis. Jafarian and Rezvani (2012) used FTA to evaluate the root causes of passenger-train derailments. Moreover, FTA was also employed by Medikonda, Ramaiah, and Gokhale (2011) in the safety-specific analysis of a Railroad Crossing Control System in order to identify potential hazardous software faults.

In this paper, the co-occurrence of two intermediate events, which are a signal displaying restricted-speed indication and the failure to comply with restricted-speed indication, would lead to restricted-speed accidents. These two intermediate events represent two primary determinants, in which each consists of a series of basic events. A signal displaying a restricted-speed

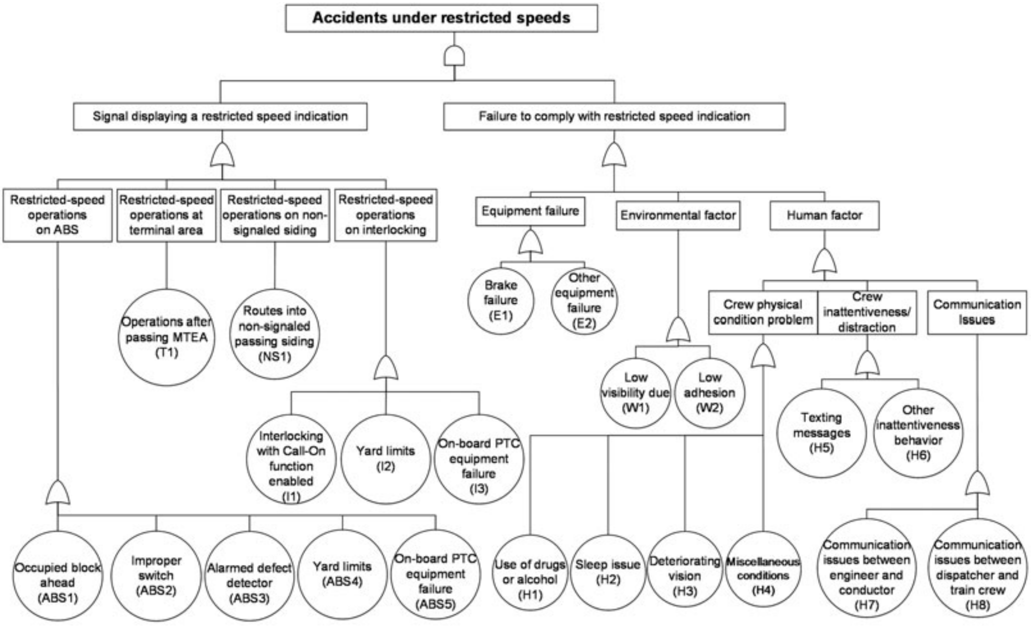

Figure 6. Fault Tree for train accidents under restricted speeds.

indication can be deducted into four major restricted-speed scenarios, including Automatic Block Signal (ABS), interlocking, non-signaled siding, and terminal area. For example, restricted speed is imposed on ABS where the block ahead is occupied, a switch is not properly lined, or a defect detector is alarmed. Interlocking involves restricted-speed operation where the Call-On function is enabled. Diverging either into non-signaled sidings from the signaled main track, or into the signaled main track from non-signaled sidings is one common form of restricted-speed operations. Moreover, the Mainline Track Exclusion Addendum (MTEA) at terminal stations requires restricted-speeds operations. In terms of failure to comply with restricted-speed indications, three major event groups exist, including equipment failure, environmental conditions, and human error. Rolling stock failure, such as brake failure, may fail to stop the train short of the stopping point. In terms of environmental conditions, low visibility due to severe weather conditions (e.g. heavy snow, dense fog) and low adhesion due to vegetation or extreme environmental conditions (e.g. snow, ice) may be contributing factors. As for human error, crewmembers' physical condition problems (e.g. use of alcohol, sleep issue, deteriorating vision), inattentive behaviors (e.g. texting), or communication problems (e.g. miscommunication or lack of communication between crews and dispatchers) may result in rule violation and thus an accident. In Figure 6, the bottom leaves of the fault tree are basic events and represent the lowest-level events that may contribute to the occurrence of the top event. To clarify, the FTA covers not only the human factor as the primary cause but also equipment failure and environmental conditions as potential contributing causes in some cases.

7. Discussions of restricted-speed accident risk mitigations

Faced with unchanged restricted-speed accident risk in the last 17 years, it is not only important, but also crucial to develop and implement safety strategies at restricted-speed train operations. Based upon the findings from the above FTA and reference information from multiple NTSB investigation reports (NTSB 2012, 2013, 2018a, 2018b), this section mainly discusses human-error preventions strategies (e.g. medical screening and alerter system) and advanced train control system (e.g. Positive Train Control (PTC)) that can enforce positive stops when human intervention fails. Moreover, bumping posts with high-impact tolerance and valid system safety program plans can also be effective risk mitigation strategies and have been discussed explicitly by Moturu and Utterback (2018) and NTSB (2018b), respectively, and thus will not be further discussed in this paper.

7.1. Prevention of human errors

7.1.1. Appropriate medical program for safety-sensitive personnel

Among the NTSB railroad accident reports that investigated restricted-speed accidents in the last five years, the violation of restricted-speed operating rules due to crewmembers' human error is one primary cause. In particular, human error due to physical condition (e.g. vision problems and sleep disorders) is identified in the developed Fault Tree as one root cause behind restricted-speed accidents. For example, in the investigation of a head-on collision of two Union Pacific Railroad freight trains in 2012, NTSB (2013) concluded this restricted-speed accident resulted from the engineer's inability to see and correctly interpret the restricting signals. In both the NJT train accident at Hoboken Terminal in 2016 and the Long Island Rail Road (LIRR) train accident at Atlantic Terminal in 2017, the investigation results indicated that both engineers in both restricted-speed accidents were operating trains despite their fatigue due to untreated obstructive sleep apnea (OSA). Consequently, NTSB has suggested an appropriate, comprehensive medical program to ensure that employees in safety-sensitive positions should follow medical standards to be fit for duty.

Accounting for vision issues in medical tests, NTSB (2013) suggested the implementation of a validated, reliable, and comparable color vision field test. Railroads should establish an acceptable medical program involving this vision test and ensure that personnel in safety-sensitive positions have sufficient color discrimination to perform safely. As for crewmembers who fail the color vision test, it would be advisable to restrict such crewmembers to working in yard assignments or unsignaled territory (NTSB 2013).

In terms of OSA and other sleep disorders, the development and enforcement of medical standards are essential, and employees with these issues should be required to undergo medical sleep-disorder-related screening and follow-up treatment. The railroad employees in safety-sensitive positions should meet the required standards in order to resume work. In both evaluation and treatment of sleep disorders, Epstein et al. (2009) provided a comprehensive clinical guideline, in which the diagnostic of OSA involves a sleep-oriented history, physical examination, and objective testing. Once the diagnosis is set up, the patient should consider an appropriate treatment strategy, which covers positive airway pressure devices, oral appliances, behavioral treatments, surgery, and/or adjunctive treatments (Epstein et al. 2009). With the experience from existing OSA screening practices in some railroads and supportive literature, a comprehensive, valid medical program can be developed to mitigate the risk that sleep disorders pose to restricted-speed operations in the national rail system.

7.1.2. Implementation of alerters

Inattentive behaviors from crew members are identified in the Fault Tree (Figure 6) as one common causal factor behind restricted-speed accidents. Such accident risk can be mitigated through an alerter, which can be implemented in the locomotive cab to promote the engineer's attentiveness through both audible alarms and visual alarms. With this safety device in the locomotive cab, if the system detects no control activity from the engineer in a predetermined time, both kinds of alarms are activated to prompt a response. Ultimately, in this way the engineer's inattentiveness may be mitigated to some degree.

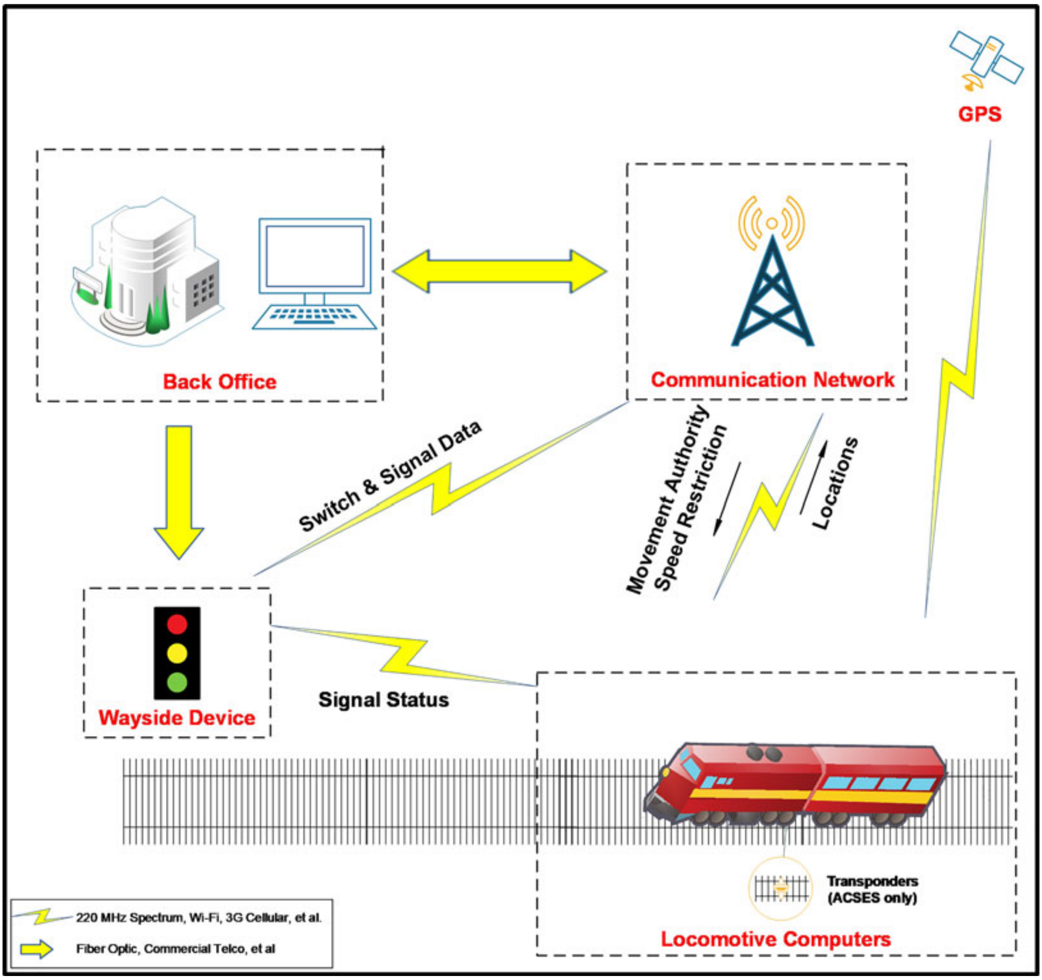

Figure 7. Architectures of a generic PTC system (Zhang, Liu, and Holt 2018).

7.2. Positive train control or alike accident prevention technologies

In order to confront human intervention failures in some cases, advanced train control systems such as PTC can be implemented to enforce positive stops and thereby prevent restricted-speed accidents. PTC is a communication-based/processor-based train control system that is capable of reliably and functionally preventing train accidents attributable to human error. Through integrating the locomotive computer, wayside device, communication network, and back office (Figure 7), the PTC system can compare train real-time conditions against movement authority and speed restriction information to ensure train safety. Whenever a train crew fails to properly operate within specified safety parameters, the PTC system automatically applies the brakes and brings the train to a positive stop (Zhang, Liu, and Holt 2018).

Federal regulations (FRA 2011b) designate train operations at restricted speeds as a regulatory exemption from the PTC requirement and accordingly state that the PTC system is not required to perform its functions when a train is traveling under restricted speeds. For example, in both the NJT accident at Hoboken Terminal and LIRR accident at Atlantic Terminal, trains operating with terminating tracks were excluded from PTC installation. Meanwhile, NTSB reports (NTSB 2013, 2018a, 2018b) pointed out that some restricted-speed accidents would have been prevented if a PTC system had been installed and used. Therefore, it is imperative that we implement mechanisms which can automatically stop a train before the occurrence of such an accident, even if the engineer is negligent or disengaged, in order to promote the safety of restricted-speed operations. PTC may be a feasible option to achieve this function. Its cost-effectiveness in preventing restricted-speed accidents shall be carefully evaluated in a separate study.

8. Conclusion

The restricted-speed operating rule is commonly employed on U.S. railroads. However, there is very little prior research regarding restricted-speed train accident safety and risk analysis. Using historical accident data in the United States from 2000 to 2016, this article analyzes the frequency, severity, and risk of restricted-speed accidents based on statistical approaches. On the American rail network, the estimated annual risks of restricted-speed accidents are approximately 32 casualties or approximately $9 million in damage costs (which only takes into account the direct damage cost to infrastructure, equipment and signals, without accounting for liability, casualty, environmental impact or business loss). In terms of temporal trending, there is no significant change in the rate, severity, or risk of restricted-speed train accidents in the past 17 years, while the overall train accident rate and the accident rates of major accident causes (e.g. broken rails, track-geometry failures) have declined substantially, suggesting the importance of further improving restricted-speed operational safety in the United States. To provide an additional insight into railroad safety and risk research, alternative accident risk measures are used, which are the mean value and Conditional Value at Risk (CVaR); compared to the mean value, the CVaR can capture the low probability but high-consequence characteristics of worst-case accidents. Furthermore, an understanding of restricted-speed train accident precursors and contributing factors has been developed in order to identify potential risk mitigation strategies, such as the prevention of human errors via medical programs and alerters, or the implementation of an advanced train control system (e.g. PTC) for automatically enforcing a positive train stop if locomotive engineers should fail to do so.

Disclosure statement

No potential conflict of interest was reported by the authors.

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Appendix. Selected high-consequence restricted-speed accidents, 2000–2016, in the United States[a]

Date	State	Railroad[b]	Speed (mph)	Fatality	Injury	Damage cost	Number of cars derailed
09/30/2000	New York	ATK	10	0	10	$183,574	2
10/31/2000	Arizona	BNSF	1	1	3	$3,708,100	7
07/18/2003	California	UP	10	0	8	$558,168	1
08/15/2003	New York	MNCW	12	0	10	$135,572	1
04/19/2004	New York	ATK	10	0	31	$80,000	1
08/30/2004	New Jersey	NJTR	14	0	4	$24,000	1
11/29/2004	Florida	CSX	33	1	2	$817,777	15
10/15/2005	Arizona	UP	17	1	46	$2,379,170	0
01/18/2006	Alabama	NS	53	0	3	$2,534,100	10
10/13/2007	Indiana	NICD	14	0	4	$2,100,000	0
11/30/2007	Illinois	ATK	33	0	136	$1,719,000	1
02/07/2008	Washington, DC	MACZ	12	0	8	$183,000	0
06/27/2008	California	ACEX	9	0	7	$18,872	1
11/14/2008	California	BNSF	11	0	5	$71,300	0
01/27/2009	Pennsylvania	SEPA	30	0	20	$700,000	0
04/17/2011	Iowa	BNSF	22	2	2	$2,276,952	4
05/24/2011	North Carolina	CSX	48	2	2	$1,457,301	11
01/06/2012	Indiana	CSX	44	0	2	$2,549,805	6
06/24/2012	Oklahoma	UP	63	3	1	$11,729,623	27
05/25/2013	Missouri	BNSF	23	0	7	$8,686,769	13
06/27/2013	New York	CSX	20	0	2	$2,406,203	21
09/25/2013	Texas	BNSF	46	0	6	$3,744,754	11
04/06/2014	Texas	UP	18	0	2	$2,301,504	1
09/29/2016	New Jersey	NJTR	21	1	110	$6,012,000	1
10/08/2016	New York	LI	50	0	0	$3,200,000	2

[a]Data sources: FRA REA database and NTSB railroad accident reports.

[b]Railroad Codes: ATK: Amtrak; BNSF: BNSF Railway Co.; UP: Union Pacific RR Co.; MNCW: Metro-North Commuter RR Co.; NJTR: New Jersey Transit Rail Operations; CSX: CSX Transportation; NS: Norfolk Southern Corp.; NICD: Northern Indiana Commuter Transportation District; MACZ: MARC Train Service; ACEX: Altamont Commuter Express Authority; SEPA: Southeastern Pennsylvania Transportation Authority; LI: Long Island Rail Road. For updates, see http://safetydata.fra.dot.gov/OfficeofSafety/publicsite/downloads/auxrr.aspx.