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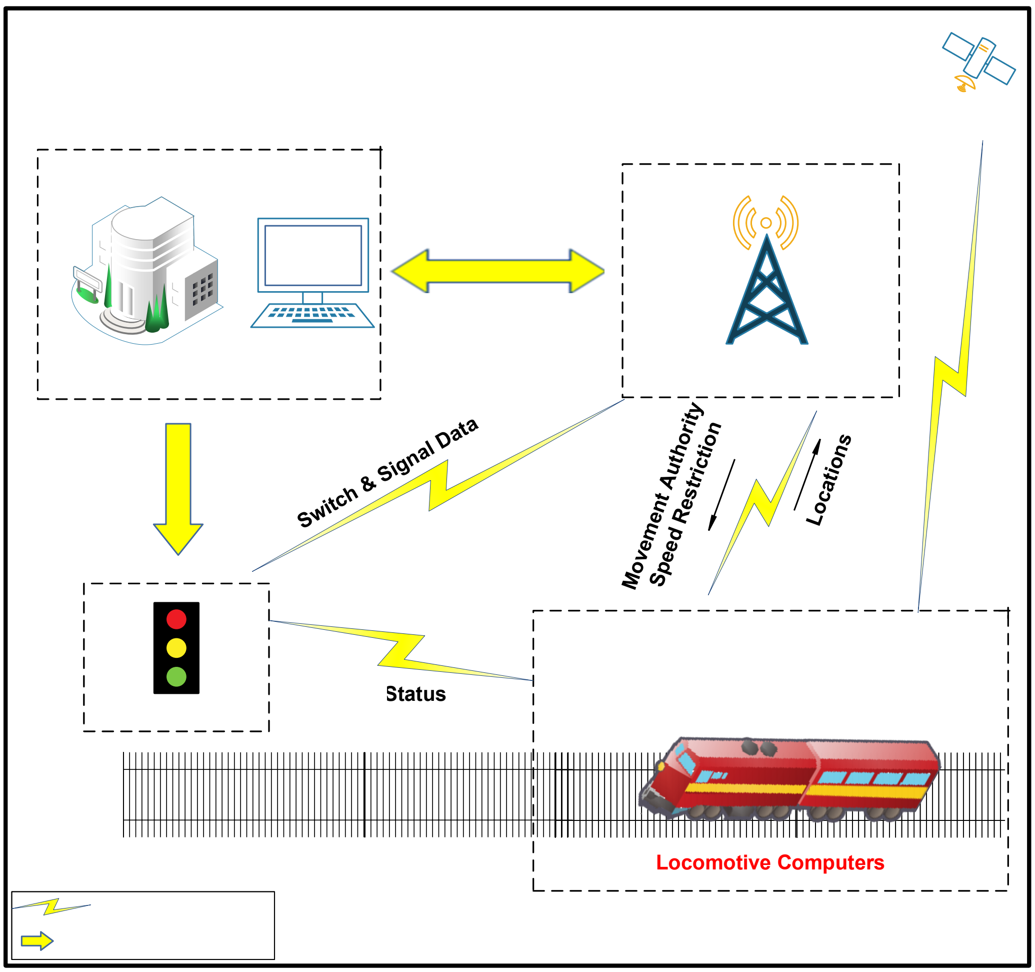
Restricted Speed Enforcement for Positive Train Control Systems



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13. ABSTRACT (Maximum 200 words) As defined by current regulations (Title 49 Code of Federal Regulations [CFR] 236 Subpart G), restricted speed is a speed that will permit stopping within one-half the range of vision, but does not exceed 20 mph. In the U.S., restricted speed operation is a common type of train operation on virtually every mile of automatic blocks and is also common in terminals and yards. From February 2017 to May 2020, the Federal Railroad Administration supported Rutgers University and HNTB Corporation in analyzing the frequency, severity, and other characteristics of restricted-speed train accidents. The team evaluated the safety benefits, incremental costs, and operational impacts of implementing Positive Train Control (PTC) in restricted-speed train operations, focusing on end-of-track collision prevention. A Concept of Operations (ConOps) was proposed, with a "what-if" scenario-based analysis for the Advanced Civil Speed Enforcement System (ACSES) and Interoperable Electronic Train Management System (I-ETMS). A benefit-cost analysis indicated that the safety benefits may exceed the incremental costs if PTC is enforced to prevent end-of-track collisions over a 20-year period under specified circumstances and assumptions. Finally, a field test plan was proposed which can be used to validate the proposed ConOps.			
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ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in)	=	2.5 centimeters (cm)
1 foot (ft)	=	30 centimeters (cm)
1 yard (yd)	=	0.9 meter (m)
1 mile (mi)	=	1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2)	=	6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2)	=	0.09 square meter (m^2)
1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)
1 square mile (sq mi, mi^2)	=	2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he)	=	4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz)	=	28 grams (gm)
1 pound (lb)	=	0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb)	=	0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp)	=	5 milliliters (ml)
1 tablespoon (tbsp)	=	15 milliliters (ml)
1 fluid ounce (fl oz)	=	30 milliliters (ml)
1 cup (c)	=	0.24 liter (l)
1 pint (pt)	=	0.47 liter (l)
1 quart (qt)	=	0.96 liter (l)
1 gallon (gal)	=	3.8 liters (l)
1 cubic foot (cu ft, ft^3)	=	0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3)	=	0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm)	=	0.04 inch (in)
1 centimeter (cm)	=	0.4 inch (in)
1 meter (m)	=	3.3 feet (ft)
1 meter (m)	=	1.1 yards (yd)
1 kilometer (km)	=	0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2)	=	0.16 square inch (sq in, in^2)
1 square meter (m^2)	=	1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2)	=	1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm)	=	0.036 ounce (oz)
1 kilogram (kg)	=	2.2 pounds (lb)
1 tonne (t)	=	1,000 kilograms (kg)
	=	1.1 short tons

VOLUME (APPROXIMATE)

1 milliliter (ml)	=	0.03 fluid ounce (fl oz)
1 liter (l)	=	2.1 pints (pt)
1 liter (l)	=	1.06 quarts (qt)
1 liter (l)	=	0.26 gallon (gal)
1 cubic meter (m^3)	=	36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3)	=	1.3 cubic yards (cu yd, yd^3)

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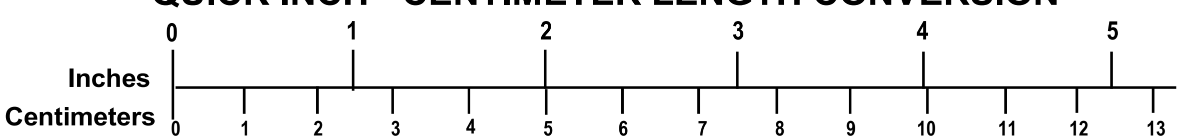

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°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

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Executive Summary

In 49 Code of Federal Regulations Part 236, restricted speed is defined as a speed that permits stopping within one-half the range of vision, but does not exceed 20 mph. While previous studies have focused extensively on the safety risks associated with high-frequency, high-consequence accidents, comparatively little prior work has been undertaken to evaluate railroad risk and safety under restricted-speed operations. Moreover, current regulations do not require Positive Train Control (PTC) to perform when a train is traveling under the restricted speed. Recently, a series of severe accidents have occurred due to violations of restricted speed rules, resulting in injuries or fatalities, infrastructure and rolling stock damage, and environmental impacts. Because of these facts and the existing research gap, researchers at Rutgers University and HNTB Corporation took great interest in understanding the safety risks of restricted-speed operation and effective strategies for accident prevention.

From February 2017 to May 2020, the Federal Railroad Administration supported the research team's efforts in analyzing the frequency, severity, risk, and other pertinent characteristics of restricted-speed accidents. The analysis showed that the rate of restricted-speed train accidents showed no significant change since 2000, while the overall train accident rate declined substantially. In addition, a micro-level study based on fault tree analysis (FTA) showed that human error mitigation actions (e.g., medical program, alert system) and advanced train control (e.g., Positive Train Control) were promising restricted-speed accident risk prevention strategies. In particular, the team proposed the potential implementation of Positive Train Control (PTC) systems in restricted-speed train operations to improve safety at restricted speeds by automatically stopping a train if the engineer is negligent or disengaged. This study primarily focused on the enforcement of the two most widely implemented PTC systems: the Advanced Civil Speed Enforcement System (ACSES) and the Interoperable Electronic Train Management System (I-ETMS). The resulting Concept of Operations (ConOps) depicted high-level system characteristics for a proposed PTC enforcement at restricted-speed train operation and presented a "what-if" scenario-based analysis.

The team analyzed the safety statistics of end-of-track collisions, then developed both FTA and Systems-Theoretic Accident Model and Processes (STAMP) to understand the causes and contributing factors of end-of-track collisions. Researchers evaluated the incremental costs, safety benefits, and operational impacts in passenger terminals. The benefit-cost analysis (BCA) showed that the safety benefits may exceed the additional installation and maintenance costs in a 20-year period. More specifically, the annualized net present value was around $800,000 (2017 dollars, 7 percent discount rate), or $1.3 million (2017 dollars, 3 percent discount rate). The BCA ratio was 1.7–2.8 (7 percent discount rate) or 1.8–3.1 (3 percent discount rate). The operating capacity was evaluated with a Monte Carlo simulation model. The results indicated that the operational impact in PTC enforcement should be negligible, except for the rare occurrence of a wayside interface unit failure or radio failure in an I-ETMS-type PTC system that would potentially result in a stop well short of the targeted point and delay both onboard passengers and inbound/outbound trains. Furthermore, the team proposed in-field test plans of the proposed PTC enforcements at terminus stations.

1. Introduction

The Rail Safety Improvement Act of 2008 (RSIA08) mandates the implementation of Positive Train Control (PTC) on railroads that carry passengers or have high-volume freight traffic with toxic- or poisonous-by-inhalation hazardous materials. As a safeguard against human error, PTC is expected to prevent train accidents attributable to human error by slowing or stopping trains automatically. PTC is designed to prevent train-to-train collisions, derailments caused by excessive speeds, unauthorized incursions into work zones, and movements of trains through misaligned railroad switches. However, even with fully implemented and functioning PTC systems, accident risks under restricted-speed train operations cannot be reduced due to regulation exemptions.

As defined by current regulations (Title 49 Code of Federal Regulations [CFR] 236 Subpart G), restricted speed is a speed that will permit stopping within one-half the range of vision, but does not exceed 20 mph. In the U.S., restricted speed operation is a common type of train operation on virtually every mile of automatic blocks and is also common in terminals and yards. From February 2017 to May 2020, the Federal Railroad Administration (FRA) supported a research team from Rutgers University and HNTB Corporation in analyzing the frequency, severity, and other characteristics of restricted-speed train accidents.

1.1 Background

In 2012, the National Transportation Safety Board (NTSB) issued a report that highlighted five rear-end collisions due to restricted speed violations (National Transportation Safety Board, 2012). One of them was a collision of a BNSF coal train with the rear end of a standing BNSF maintenance-of-way equipment train in Red Oak, IA, on April 17, 2011. As a result of train-to-train collision, both crewmembers on the striking train were fatally injured and the damage cost was more than $8 million. On January 4, 2017, a Long Island Rail Road (LIRR) passenger train collided with the platform in the Atlantic Terminal in New York City. This accident occurred inside the terminal (where traveling under restricted speeds is required) and led to 108 injuries and around $5.3 million in damage (National Transportation Safety Board, 2018b). However, current regulations (49 CFR 236 Subpart I) do not require PTC to perform its functions when a train is traveling under restricted speeds. These facts and lack of research on this topic have generated interest in understanding restricted-speed operation safety risks and effective accident prevention strategies.

As a safeguard against human error, PTC is expected to prevent train accidents attributable to human error, by slowing or stopping trains automatically. PTC is designed to prevent:

- Train-to-train collisions
- Derailments caused by excessive speeds
- Unauthorized incursions into work zones
- Movements of trains through misaligned railroad switches

Complying with the requirements of Subpart I in the Code of Federal Regulations (CFR, 2011), the territory of PTC implementation and operation includes Class I railroads, main lines servicing over 5 million gross tons (MGT) annually and over which toxic- or poisonous-by-inhalation hazardous materials are transported, and main lines involving intercity and commuter passenger trains. The full implementation of PTC involves around over 60,000 route miles (AAR, 2017). The large-scale, network-level PTC implementation affects the U.S. rail industry in several aspects, in terms of implementation cost, operational impact, and safety effectiveness (FRA, 2009; Van Dyke and Case, 2010; Peters and Frittelli, 2012; Zhao and Ioannou, 2015: AAR, 2017).

PTC integrates various components (Figure 1), namely the locomotive computer, wayside device, communication network, and back office (APTA, 2015; AAR, 2017).

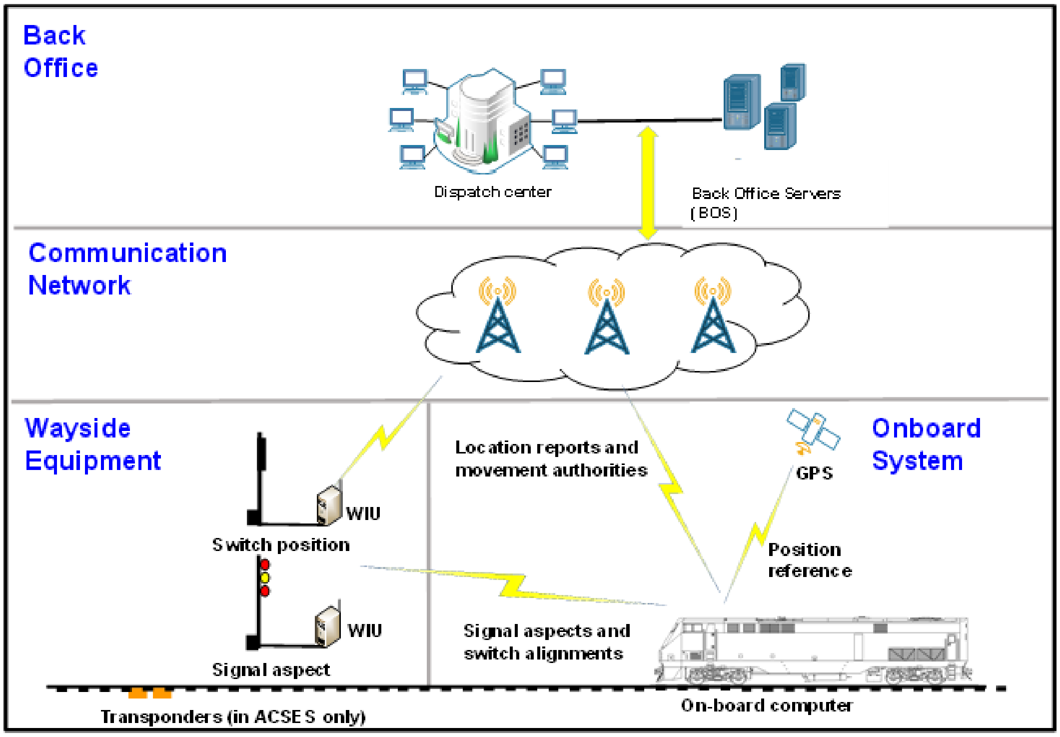


Figure 1. Schematic Illustration of a General PTC System

The locomotive computer accepts speed restriction information and movement authority so that these data can be compared against the train's location to ensure compliance. The wayside device on the side of the track is capable of monitoring and reporting switch position and signal status to locomotive computers and the back office. The back office is a centralized location for the communication and coordination of train orders, speed restrictions, train information, track authorities, crew sign-in and sign-off, and bulletins, as well as specialized data to and from the wayside and train operational and safety data (GAO, 2015). Three main parts of the back-office system, namely back office server (BOS), geographical information system (GIS), and dispatch office, interface with other components of the PTC systems. The BOS is a warehouse for various information systems, such as track composition, train consist, and speed limits, to support train operation. Overall, the back office provides the proper speed restriction information and movement authority to the locomotive computer. In the Advanced Civil Speed Enforcement System (ACSES), transponders are used for location tracking, permanent speed restriction (location, speed, and prevailing grade), maximum authorized speed (MAS) restriction, and telling the train when to communicate with the wayside interface unit (WIU) at the interlocking ahead. Apart from these components, PTC systems have a communication network capable of transmitting and receiving the data necessary to support an interoperable PTC network.

Communications technologies (e.g., 220 MHz radio, Wi-Fi, or cell modems) are commonly used to communicate train locations, speed restrictions, and movements.

Integrated with these components, PTC systems use a combination of communication networks, Global Positioning System (GPS) (or transponders), and fixed wayside signal devices to send and receive data about the location, direction, and speed of trains. Back offices process these data in real time and provide movement authority and speed restriction information to locomotive computers. Then locomotive computers accept the information and compare it against the train's condition to ensure safety compliance. Whenever a train crew fails to properly operate within specified safety parameters, PTC systems automatically apply the brakes and bring the train to a stop.

Rather than one single technology, PTC describes a suite of train control standards. Railroads in the U.S. are allowed to install different PTC technologies in their respective systems once the types are approved and certified by FRA, including ACSES, I-ETMS, Enhanced Automatic Train Control (E-ATC), Incremental Train Control System (ITCS), Communications Based Train Control (CBTC), SafeNet System, and Sentinel System. In previous research, Hann (2010) introduced ITCS—in particular, its wireless grade crossing activation and communications. CBTC was introduced with a summary overview by Pascoe and Eichorn (2009) and a focus of data communication subsystems by Fitzmaurice (2013). Among these systems, ACSES and I-ETMS are the two most widely used PTC systems. This article would focus on the potential passenger terminal enforcement of ACSES system and I-ETMS system that cover a vast majority of the PTC systems installed in the U.S.

1.1.1 ACSES-Type PTC System

An ACSES system works in conjunction with an existing Automatic Train Control (ATC) system; together, the two provide FRA-approved PTC implementation. Specifically, the ATC system ensures safe train separation and signal speed enforcement, while the ACSES acts as an overlay to enforce civil speed restrictions (the maximum speed authorized for each section of track), temporary speed restrictions (e.g., temporary work zone), and positive train stops (PTS).

One major feature of ACSES-type PTC system is the employment of transponders. Differing from most types of PTC systems that use GPS to identify train positions, ACSES establishes an exact position from the transponder sets it encounters. Passive, fixed transponders are placed between the rails along the right-of-way (ROW) and are composed of 2-4 physical transponder devices (Figure 2) to improve reliability, increase information capacity, and provide identification of traffic direction. As passive devices, transponders require no wayside power supplies and are programmed by means of a "plug" inserted into them. An antenna underneath the locomotive picks up the information contained in the plug. The information package involves maximum authorized speed, civil speed restrictions, track length of speed restriction, linking distances to the next transponder set, etc. Between transponder sets, train positioning is ascertained by counting the speed pulses from the tachometer, or known as "dead reckoning." Any accumulated error is reset when the train encounters the next transponder set. Overall, with transponders installed at home signals, pre-distance signals, or block points, the train movement speed and movement authorization can be kept safe and compliant for the various types of operation rules and restrictions. A PTS would be enforced by ACSES if noncompliant train operations occur.

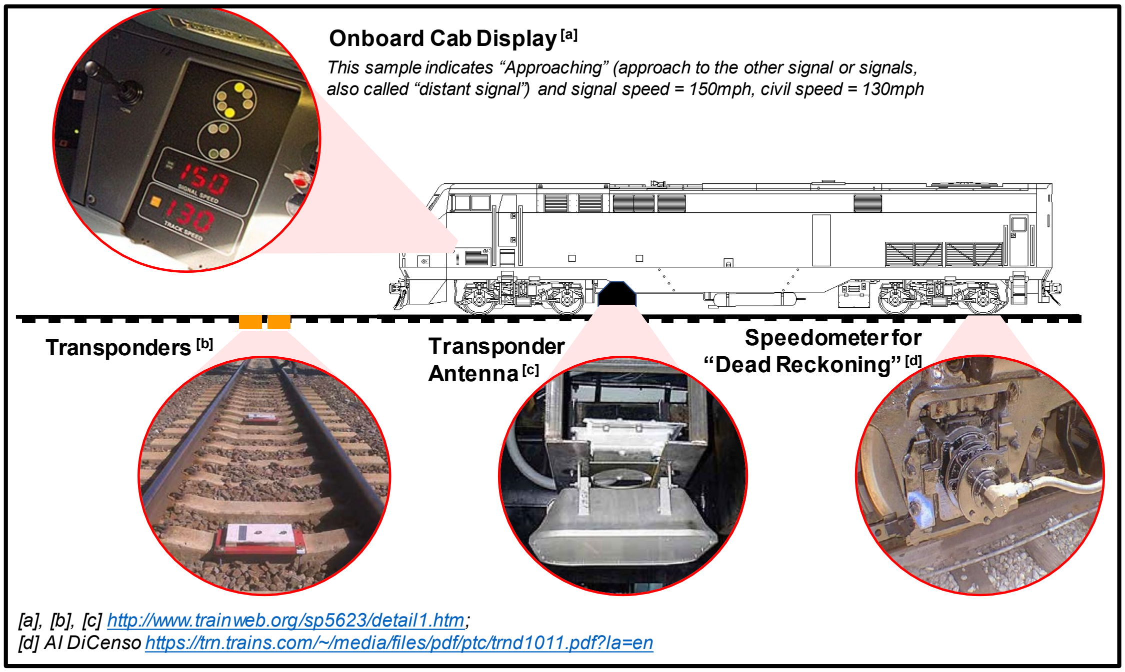


Figure 2. Onboard Locomotive System in ACSES-Type PTC System

1.1.2 I-ETMS-Type PTC System

In an I-ETMS system, the civil data information for the entire designated route should be preloaded in advance of the trip. The essential data information is collected through track mapping. In this preparation work, a variety of track field assets (e.g., signals, mileposts, switches, locations of curves, grade crossing, and speed change points) are mapped and stored in the subdivision file to support a high-accuracy GIS. The periodic extraction of GIS data contributes to keeping civil data up to date.

After the I-ETMS locomotive initialization, the GPS would provide the train location and navigation, which are received by the locomotive system using onboard antennas. The WIU would convert the status of wayside signal equipment and switch position along the ROW into a serial information message, which is then transmitted to the approaching onboard locomotive systems (Thurston, 2013). Then the locomotive segment would monitor the train real-time movement authority and speed based on the collected information. The system would allow to proceed only if the switches are properly aligned, and the speed limit is strictly followed. The unauthorized movement, overspeed train movement, or misaligned switch would result in penalty brakes to slow down or even enforce a PTS.

1.2 Objectives

To the team's knowledge, prior research focusing on end-of-track collision risk management is limited. The primary objective of this research was to analyze the potential implementation of PTC to prevent end-of-track collisions at passenger terminals, with a focus on Concept of Operations (ConOps), safety benefit, cost, and operational impact.

1.3 Overall Approach

The research team used various methodologies, including statistical analysis, accident analysis, cost-benefit analysis, and simulation. Initially, negative binomial (NB) regression models were used to assess restricted-speed accident rate and severity. Moreover, the overall accident risk was modeled using expected value, value at risk (VaR), and conditional value at risk (CVaR), respectively. Subsequent analysis of these accidents involved Fault Tree Analysis (FTA) and Systems-Theoretic Accident Modeling and Processes (STAMP) to identify contributing factors and safety constraints in specific accidents.

The team also introduced a ConOps to explore potential applications of PTC in preventing restricted-speed train accidents. A benefit-cost analysis (BCA) was developed to quantify expected benefits and costs associated with implementing PTC at stub-end terminals. Finally, the research utilized Monte Carlo simulation to assess the potential operational impact of PTC on train operations at stub-end terminals.

1.4 Scope

This research considers both freight and passenger trains. However, the benefit-cost analysis conducted in this research does not account for possible business losses or environmental impacts associated with restricted-speed accidents. In addition, within the concept of operations, the proposed modifications for each restricted-speed scenario exclude potential software updates in the back office and locomotive.

1.5 Organization of the Report

This report is organized as follows:

- Section 1 introduces the research and work conducted.
- Section 2 presents the safety risk analysis of restricted speeds.
- Section 3 describes end-of-track collisions at terminating stations as one focused scenario.
- Section 4 presents a systematic analysis of end-of-track collisions with the STAMP model.
- Section 5 demonstrates the ConOps for PTC enforcement in the prevention of end-of-track collisions.
- Section 6 provides the BCA of the proposed ConOps.
- Section 7 presents the operational impact assessment.
- Section 8 delivers the field test of PTC implementation at terminating stations.
- Section 9 presents the conclusions of this study.

2. Restricted Speed Train Accident Risk Analysis and Prevention

2.1 Introduction

Railroads play a key role in the transportation infrastructure and economic development of the U.S., and safety is of the utmost importance. In the U.S., train accident analysis has primarily focused on derailment, hazardous material releases, and highway-rail grade crossing accidents (Anderson and Barkan, 2004; Liu et al., 2011; Chadwick et al., 2014; Liu, 2016a; Liu, 2016b). However, much less research has evaluated train risk and safety for restricted-speed train accidents, even though restricted speed violations are common on U.S. railroads and can cause high consequences under certain scenarios.

The 49 CFR 236 Subpart G regulation mandates 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 U.S., restricted-speed operation is a common type of train operation, which is on virtually every mile of the Absolute Block System (ABS) and used extensively at 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, a 2012 NTSB report highlighted five rear-end collisions caused by restricted-speed violations (NTSB, 2012).

Despite this ubiquitous risk, prior research analyzing restricted-speed train accidents in the U.S. is quite limited. This knowledge gap motivated the development of this section, which examines U.S. restricted-speed train accidents caused by human factors, with a focus on two aspects: 1) a macro-level analysis of nationwide restricted-speed accident risk in the U.S., and 2) micro-level FTA of individual accidents. Based on prior studies on accident risks (Aven and Renn, 2009; Liu, 2016), the risk of restricted-speed accidents was 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 using the expected consequence (mean value) to represent the risk, alternative risk measures (specifically the conditional value at risk) were developed to characterize low-probability-high-consequence restricted-speed train accidents under certain circumstances. Apart from a macro-level analysis of nationwide restricted-speed accidents, FTA was also developed based on specific accidents to explore the characteristics of individual accident cases. This aided in the development of a micro-level analysis.

2.2 Relevant Literature

Rail risk analysis and accident prevention have long been a priority for the railroad industry. Numerous studies have concentrated on train risk analysis associated with train derailment (Barkan et al., 2003; Bagheri, 2011) or highway-rail grade crossing accidents (Austin and Carson, 2002; Chadwick et al., 2014), and some work has been undertaken to evaluate train collision risk (Liu, 2016a). These three types of incidents comprise the leading accident categories on U.S. railroads. In addition, extensive studies (Ahmad et al., 2013; Lin et al., 2014) have identified the contributing causes in train accidents, including track, rolling stock, signal, human factors, and other miscellaneous factors (e.g., environmental conditions). Still, research on other specific types of train accidents is lacking, such as those under restricted-speed operations.

2.3 Data Sources

The accident data used in this study came from the FRA's Rail Equipment Accident (REA) database. 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, periodically adjusted for inflation, increased from \$6,600 in 2001 to \$10,500 in 2016 (FRA, 2018a). 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 used 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 was used to calculate derailment rate, which is defined as the number of derailments normalized by traffic volume (Anderson and Barkan, 2004; Liu, 2016b). 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.

2.4 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 were the criteria used to identify restricted-speed accidents. A railroad representative provides a short written description of the accident. In these accident narratives, keywords such as "restricted speed" or "restricting signal" are adopted to collect restricted-speed accidents. Accident causes were compiled into two fields – 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 likely indicate a restricted-speed accident. Per railroad experts, three cause codes, H603, H605, and H607, have a relationship with restricted-speed accidents due to human error (FRA, 2018a) and are used in this study. Descriptions of them are as shown in Table 1. The definitions of yard limits and interlocking 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.

Table 1. FRA Accident Cause Codes Related to Accidents at Restricted Speeds (FRA, 2011b)

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

In addition, the accident narratives were manually reviewed to verify that the accidents cited were indeed due to violations of restricted-speed operating rules (e.g., operating the train above 20 mph in the restricted speed territory). Figure 3 presents a general flowchart for restricted-speed accident data collection. 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 accidents include both freight train accidents and passenger train accidents on all types of tracks (e.g., main, yard, siding, and industry).

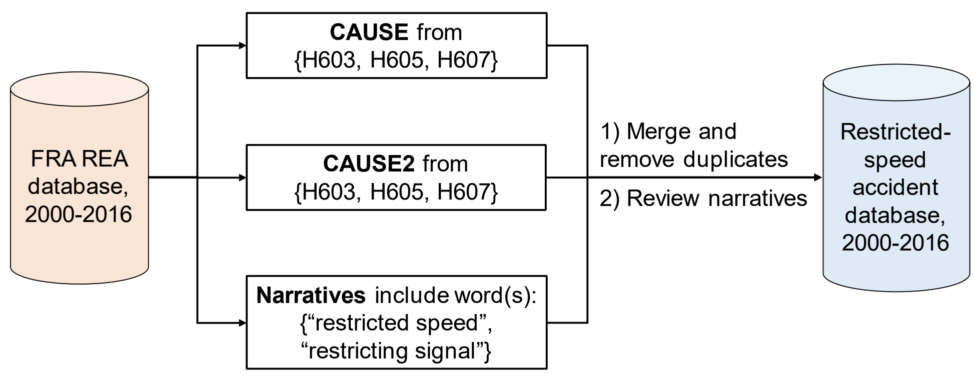


Figure 3. Restricted-Speed Accident Data Collections

2.5 Accident Rate and Severity Analysis

Based on the FRA data from 2000 to 2016, on average, there were 52 restricted-speed accidents per year in the U.S. In the 17-year study period, those restricted-speed accidents 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) to account for inflation, the total cost of damage was around $146 million (in 2016 dollars) in this period. Most of those restricted-speed accidents occurred in the form of either derailments or collisions, each accounting for 39 percent, 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 percent of restricted-speed train accidents. The statistical analysis of accident frequency, severity, and risk (measured by casualty or damage cost) will be discussed in the following subsections (Figure 4).

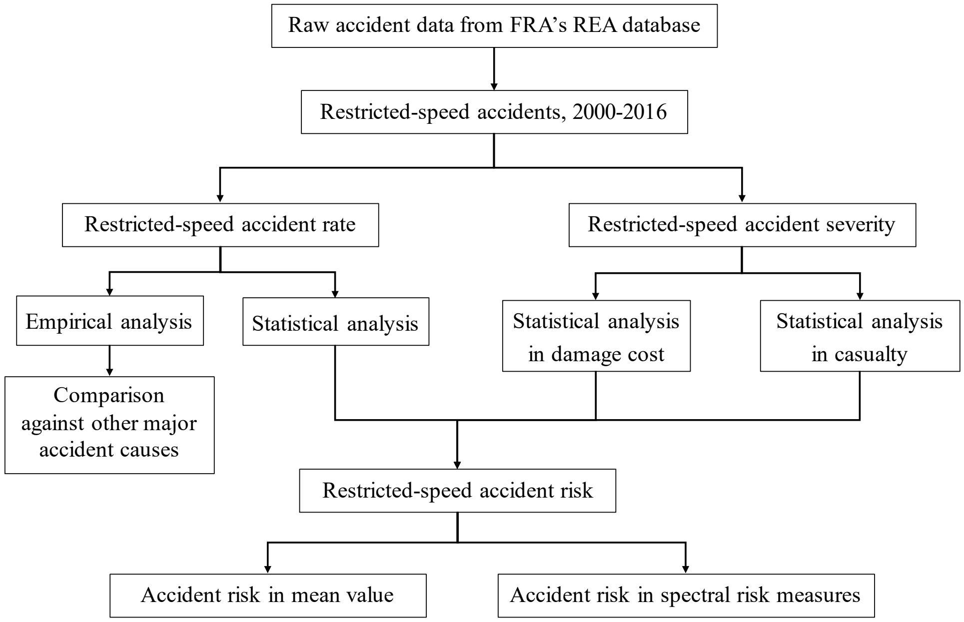


Figure 4. Flowchart of the Methodology Implemented

2.5.1 Restricted-Speed Accident Rate

Figure 5 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.

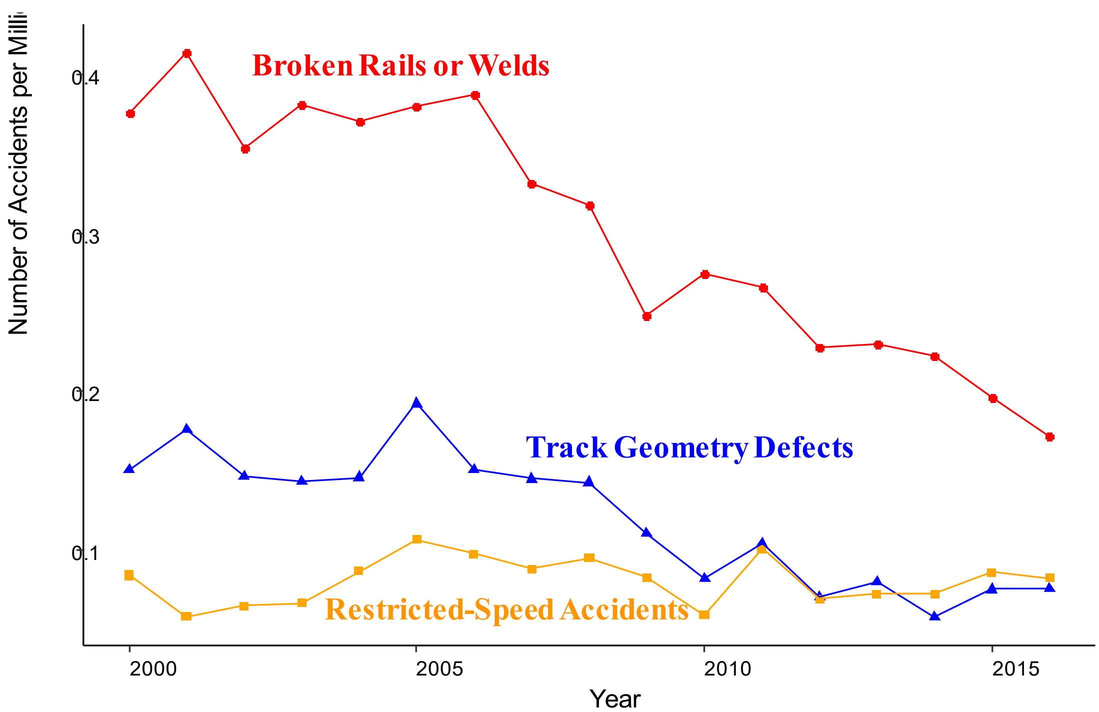


Figure 5. Temporal Trend in Accident Rates for Three Accident Groups in the U.S., 2000–2016

While broken rails have been the leading accident cause in the U.S. for the last 17 years, the rate for this cause has declined steeply, dropping by around 50 percent. A significant safety improvement has 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, U.S. railroads have invested extensively in advanced track detection technologies and risk-based maintenance strategies to increase infrastructure quality (Barkan et al., 2003). 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 surpassed that of track-geometry-defect-caused accidents since 2013.

A statistical model can estimate the restricted-speed train accident rate. Based on a prior study, this study accounted for two potential contributing factors, the year and annual traffic exposure (Liu, 2016b). 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 (Mitra and Washington, 2007) and railway transportation (Liu et al., 2017) and showed promising results with an acceptable goodness-of-fit. Therefore, it is employed to model the number of restricted-speed accidents in the U.S. Specifically, 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 et al., 2013). The model output is the number of accidents given traffic exposure, and the predictor variables are influencing factors that affect the accident rate.

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

$$y_i = \exp\,(\alpha + \beta \times T_i + \gamma \times M_i) M_i \tag{2-1}$$

Where

y_i = expected number of restricted-speed accidents in year i

T_i = year index

M_i = million train miles in year i

α,β,γ = parameter coefficients.

Three parameter coefficients, α, β, and γ, are estimated using the method of maximum likelihood (ML) (Hosmer et al., 2013). The model 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 percent, 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 statistically 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 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.

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

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 fit the empirical data in this study. The analysis showed that there is a non-linear relationship between the restricted-speed accident rate (y_i/M_i) and traffic volume (train miles, M_i). When traffic exposure increases, the restricted-speed accident rate per train-mile also increases, probably due to the increased opportunities for train encounters (Nayak et al., 1983).

A sensitivity analysis was conducted here to estimate the restricted-speed accident rate given different traffic levels. If there is an annual 3 percent 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 percent accident rate reduction. Inversely, an annual 3 percent increase in baseline traffic volume can lead to a 5 percent accident rate boost in restricted-speed accidents.

2.5.2 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 et al., 2010), and the number of cars derailed—a common metric in studies on derailment (Barkan et al., 2003; Liu et al., 2012). In this study, two proxy variables were employed to measure the severity of restricted-speed accidents: the number of casualties and the damage costs. Other proxies for accident consequence, such as business losses and environmental impacts, vary among accidents; this information was 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 was taken into consideration and the damage cost 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 each year. A Wald-Wolfowitz runs test was 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 casualty (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 used the average restricted-speed accident severities, which are 0.545 casualties per accident and around $165,000 in damage per accident.

Table 3. Restricted-Speed Accident Severity in Casualties and Damage Cost per Accident, 2001–2017

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

2.6 Accident Risk Analysis

2.6.1 Mean Value as Risk Measure

Several previous studies have defined risk as the combination of possible consequences and associated probabilities (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, annual restricted-speed accident risk is defined as the total expected number of casualties or damage costs each year. The risk is equivalent to the expected summations of either casualties or damage costs (accident severity,

X_{ij}) for all restricted-speed accidents in one year (accident severity, N). Both accident frequency (N) and severity (X_{ij}) are random variables. Using the Law of Total Expectation (Weiss, 2006),

$$E(\sum_{j=1}^{N} X_{ij}) = E\left[E(\sum_{j=1}^{N} X_{ij} | N = n)\right] = E\left[NE\left(X_{ij}\right)\right] = E(N)E\left(X_{ij}\right) \tag{2-2}$$

Where

$$i = \begin{cases} 1, & \text{using number of casualties as accident severity metric} \\ 2, & \text{using damage costs as accident severity metric} \end{cases}$$

R_{1i} = annual restricted-speed accident risk (mean) based on the severity metric used

N = number of restricted-speed accidents in one year

X_{ij} = accident severity, either in casualty or damage cost

According to above equation, the annual accident risk is numerically equal to the product of expected accident frequency and expected severity. $\mathrm{E}(N)$, as the expected value of accident frequency with a Negative Binomial 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 2.4.

2.6.2 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 percent of restricted-speed accidents occurred with no casualties, yet 5 of the restricted-speed accidents resulted in over 20 casualties (Figure 6). 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). Two types of SRMs, value at risk (VaR) and conditional value at risk (CVaR), are used primarily in financial engineering (Soleimani et al., 2014), social sciences (Cotter and Dowd, 2006), highway hazardous materials transportation (Toumazis and Kwon, 2016), and, recently, rail transport of hazardous materials (Hosseini and Verma, 2017). These studies found that VaR and CVaR are useful alternative risk measures to capture the "worst-case-average" of accident consequences. To the researchers' knowledge, no study to date has applied 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 (ES), is 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 percent of train accidents in terms of the number of casualties. Overall, VaR gives a range of potential losses and CVaR gives an average expected loss within the most severe accidents.

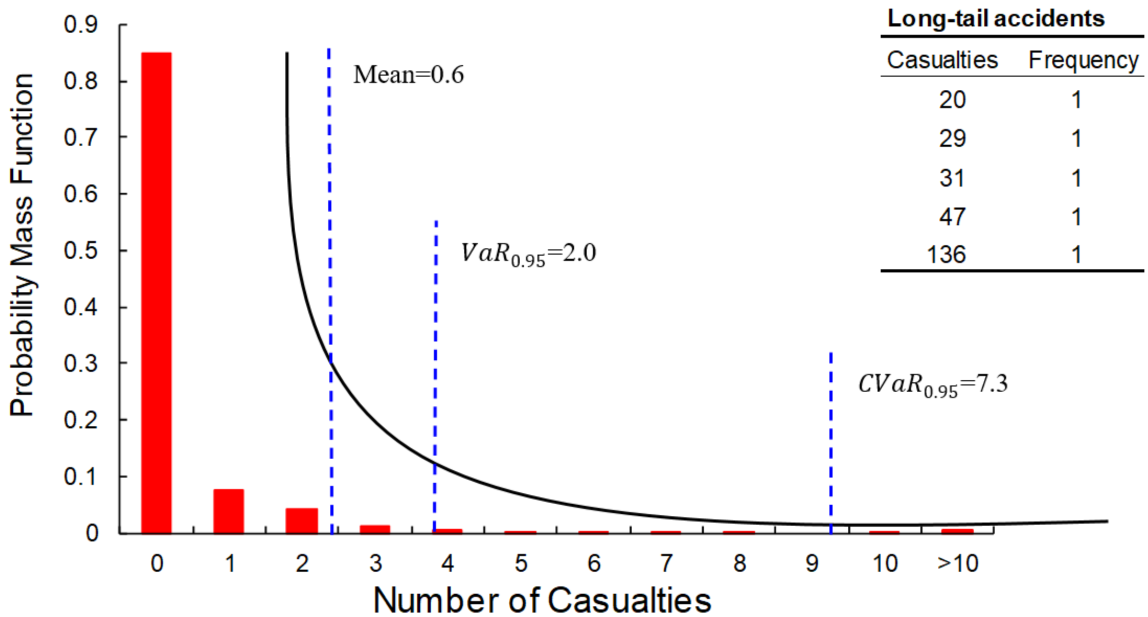


Figure 6. Distribution of Average Casualties per Restricted-Speed Accident, 2000–2016

Previous studies stated that VaR does not account for the losses/consequences beyond the threshold amount indicated by the measure (Rockafellar and Uryasev, 2000). It also has undesirable mathematical characteristics, such as a lack of subadditivity and convexity. Also, VaR is difficult to optimize when calculated from scenarios (Rockafellar and Uryasev, 2000). As an alternative measure of risk, CVaR displays superior properties compared 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 spectral risk measures as well. This research considered $CVaR_{95\%}$, which represents the mean of the 5 percent most severe (in terms of either damage costs or casualties) restricted-speed train accidents. The annual risk is defined as follows:

$$R_i = CVaR_{95\%}\left(\sum_{j=1}^{N} X_{ij}\right) \tag{2-3}$$

Where

$$i = \begin{cases} 1, & \text{using number of casualties as accident severity metric} \\ 2, & \text{using damage cost as accident severity metric} \end{cases}$$

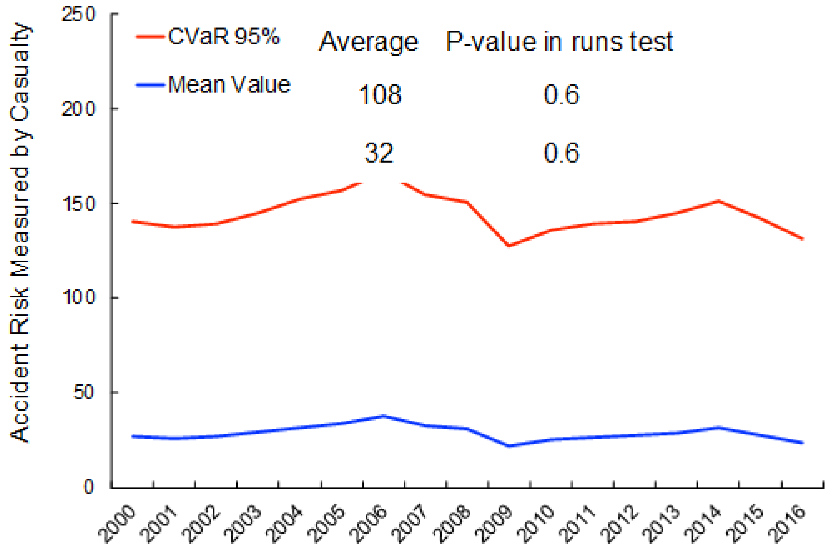
R_i = annual restricted-speed accident risk (spectral risk measure) based on severity metric used

N = number of restricted-speed accidents in a specific year

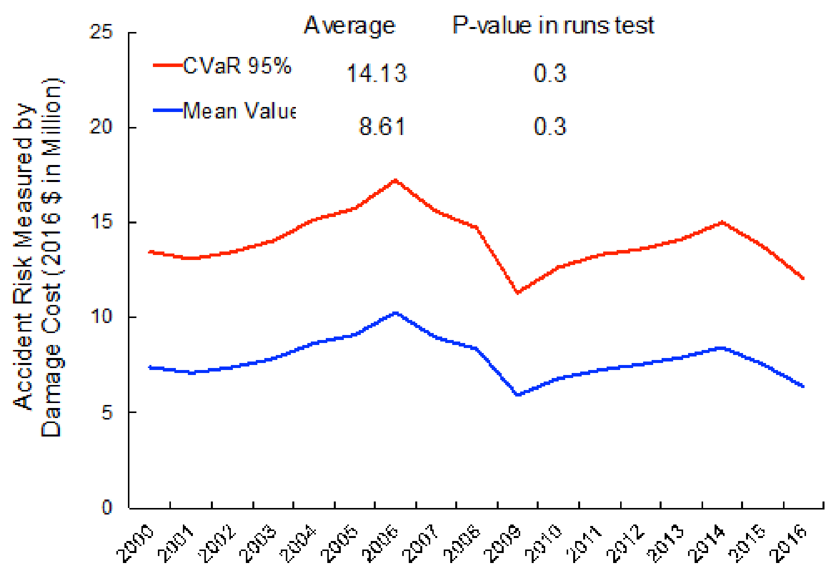
X_{ij} = accident severity (e.g., casualty or damage cost)

2.6.3 Risk Analysis Results

The accident risks are summarized in Figure 7. 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 percent 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 measures, R_{1i} (mean) and R_{2i} (CVaR), had no significant temporal trends in the study period.



(a) Accident risk in casualty



(b) Accident risk in damage cost

Figure 7. Annual Restricted-Speed Accident Risk in Mean and CVaR, 2000–2016

In the period, on average, the annual restricted-speed accident risk totaled 32 casualties or $8.61 million in damage to infrastructure and rolling stock. By contrast, on average, the worst 5 percent of restricted-speed accidents were expected to cause 108 casualties or $14.13 million in damage costs annually. Furthermore, the ratio of CVaR to mean value in casualties was over 3 times larger than the ratio of CVaR-to-mean value in damage costs (which was 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, where 85 percent 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.

2.7 Micro-Level Analysis

In addition to nationwide restricted-speed accident risk analysis in the previous sections, a micro-level analysis of restricted-speed train accidents was conducted for this section to identify the causal factors and logic paths that contribute to restricted-speed accidents. To that end, FTA was employed to visually describe the individual restricted-speed accidents based on data from the 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, it is easy to read and understand, with qualitative descriptions of potential problems and a combination of multiple events causing specific problems of interest. As one common risk assessment technique, it has been widely used in a variety of previous railway risk studies. For example, Lin et al. (2014) studied the adjacent-track accidents by using Boolean algebra based upon the results from the FTA.

The co-occurrence of two intermediate events – a signal displaying a restricted-speed indication and the failure to comply with restricted-speed indication – would lead to restricted-speed accidents. Both represent two primary determinants, consisting of a series of basic events. A signal displaying a restricted-speed 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) at terminal stations requires restricted-speeds MTEA 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 not 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 8, 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.

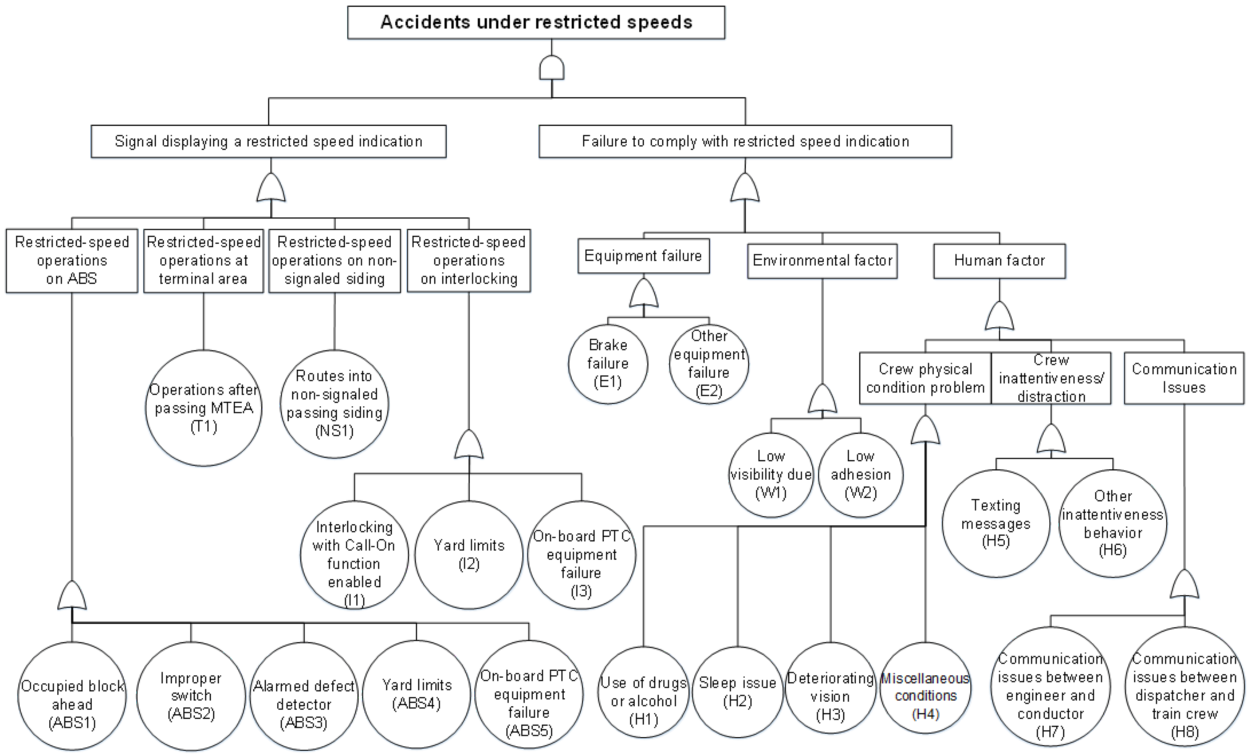


Figure 8. Fault Tree for Train Accidents under Restricted Speed

2.8 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 U.S. from 2000 to 2016, this section analyzed 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 and approximately $9 million in damage costs (which only considers 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 U.S. To provide additional insight into railroad safety and risk research, alternative accident risk measures are used, which are the mean value and 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.

3. End-of-Track Collisions at Terminus Stations

3.1 Overview of End-of-Track Collisions

Train operations at stub-end terminals are one of the common restricted-speed scenarios in the U.S. In an FRA Safety Advisory (FRA 2016), train operations in terminals with stub-end tracks are highlighted and "stress to passenger and commuter railroads the importance of taking action to help mitigate human factor accidents, assist in the investigation of such accidents, and enhance the safety of operations in stations and terminals with stub end tracks."

In the U.S., over 35 passenger terminals have multiple terminating tracks ending at bumping posts and/or platforms (NTSB, 2018a). A bumping post, also known as a bumper block or buffer stop, is an attenuating safety device at the end of the terminating track to stop authorized movement. At these passenger terminals, engineer behavior plays a key role to safely stop the train before reaching the end-of-track. However, human errors and noncompliant behaviors (e.g., disengaged, incapacitated, inattentive) may result in accidents.

A bumping post is placed at the end of terminating track to stop unauthorized movement and can provide limited protection for low-speed impacts. Passenger stations commonly comprise multiple platforms, crowded with people who are exposed to potential hazards resulting from noncompliant train operations. For example, with its 21 tracks and 11 island platforms, New York's Penn Station is the busiest passenger transportation facility in the U.S. It had a ridership of over 300,000 on the average weekday in 2016, of which LIRR contributes approximately 233,000 (LIRR, 2017). As major transportation hubs in the New York metropolitan area, the Hoboken Terminal has 17 passenger tracks and Newark Penn Station has 8 tracks; New Jersey Transit (NJT) provided around 15,600 passenger boardings and 28,000 passenger boardings, respectively, per weekday according to NJT (2018).

In the past decade, there has been a series of end-of-track collisions in passenger terminals. LIRR trains caused 15 collisions with bumping posts at passenger stations in New York between 1996 and 2010, and NJT reported 7 end-of-track collision accidents in the last 10 years (NTSB, 2018a). Most recently, the NJT train accident at Hoboken Terminal (Figure 9a) in New Jersey on September 29, 2016, led to 1 fatality, 156 injuries, and approximately $6 million in damage. A similar end-of-track collision occurred at the LIRR Atlantic Terminal (Figure 9b) in New York on January 4, 2017. It injured 112 passengers and crewmembers, and total damage costs were estimated at $5.3 million (FRA, 2018a). The engineers in both accidents failed to stop trains before reaching the end-of-tracks at passenger terminals.

NTSB stated that the safety issues identified from these two accidents also existed throughout the U.S. at many intercity passenger and commuter train terminals.

This section addresses the following questions:

1) What are the recent, historical U.S. safety statistics on end-of-track collisions?
2) What are the causes, contributing factors, and circumstances of end-of-track collisions?
3) If PTC is enforced to prevent end-of-track collisions, what is the ConOps?

The answers to these questions would explain the characteristics and probable causes of end-of-track collisions at passenger terminals as well as how PTC may be implemented to mitigate end-of-track collision risk.

Due to the complexity of this subject, this research focused on PTC enforcement to prevent end-of-track collisions due to human errors, instead of discussing all potential issues (e.g., train-to-train collisions, mechanical brake failures, broken rails). The following caveats apply:

- This research only focused on PTC enforcement on terminating tracks. The research team does *not* intend to propose PTC everywhere within a passenger terminal because of the proximity of signals and switches as well as the complexity of the track work.
- This research focused on the passenger railroads and intercity or commuter passenger railroads which are regulated by FRA.
- Apart from employing the PTC system, end-of-track collision risk may also be mitigated through other risk mitigation strategies. Alternative safety improvement strategies can be studied in future research to improve the safety of passenger terminals.

(a) NJT Accident **(b) LIRR Accident**

Figure 8. Train Accidents at (a) NJT at Hoboken Terminal and (b) LIRR at Atlantic Terminal (NTSB, 2018a)

3.2 Literature Review

Extensive research has concentrated on train safety analysis related to train derailments (Barkan et al., 2003; Bagheri et al., 2011), train collisions (Liu, 2016), and highway-rail grade crossing accidents (Austin and Carson, 2002; Chadwick et al., 2014). Although various types of train accidents have received attention in the literature, end-of-track collisions at passenger terminals rarely have been studied. In U.S. railroads, trains approaching terminating tracks are required to operate under restricted speeds, which are defined as a speed that permits stopping within one-half the range of vision but not exceeding 20 miles per hour (FRA, 2011a; GCOR, 2010; NORAC, 2018). However, “stopping within one-half the range of vision” is practically challenging, because precise stopping distances vary with environmental conditions (e.g., ice, fog), track characteristics (e.g., track gradient), and train conditions (e.g., wear of the brake pads) (Barney et al., 2001; Simith et al., 2011). Safely stopping a train on a terminating track usually relies on the attentiveness and compliance of the train crew. Some safety devices (e.g., alerter, bumping posts) have been implemented to reduce the likelihood and consequences of restricted speed violations. For example, an alerter is a safety device in the locomotive cab that is used to promote the engineer's attentiveness. If the system detects no control activities in a predetermined time, both audible and visual alarms are activated to prompt a response (NTSB, 2018a). Bumping posts are safety devices placed at the end of terminating tracks to provide limited protection for low impacts. Previous studies (NTSB, 2018a; Moturu and Utterback, 2018) stated that bumping posts did not provide adequate protection at passenger terminals and may fail at speeds over 10 mph.

3.3 End-of-Track Collision Safety Analysis

Table 4 presents a sample of recent end-of-track collisions at U.S. terminals from 2011 to 2017. The train accident information summarized here is drawn from the REA database (FRA, 2018a) and NTSB railroad accident reports. For the REA database, railroads are required to submit reports of accidents that exceed a monetary threshold for damage and loss (e.g., $10,500 in 2017). In addition to the basic accident information listed in Table 4, more comprehensive information can be found in the REA database, including operational factors, environmental factors, train characteristics, damage costs, and narratives. Additionally, NTSB reports describe accident details, factual data analysis, the (probable) cause of the accident, and safety recommendations. Instead of covering all railroad accidents, only the accidents with a significant loss of life, physical damage, important issues to public safety, or public interest are involved in the NTSB investigations (NTSB, 2018b) and then compiled into its reports.

As shown in Table 4, from 2011 to 2017, 11 end-of-track collisions were collected from the REA database and NTSB investigation reports. In the U.S., each passenger terminal has many train stops every day. For example, Chicago Union Station serves both Amtrak and Metra; hundreds of trains enter Chicago Union Station and other major terminal hubs every day. This large traffic exposure poses the potential risk of end-of-track collisions, although the probability is (fortunately) low. However, collisions occurring between 2011 and 2017 led to 310 casualties (injuries and fatalities) and over $13,745,548 in damage. In terms of either casualties or damage cost, the most severe accidents (the LIRR train accident at Atlantic Terminal and the NJT train accident at Hoboken Terminal) took place in the last 2 years and each led to over 100 casualties and over $5 million in damage to rolling stock and infrastructure. Both were caused by operational violations by the engineers, who both had Obstructive Sleep Apnea (OSA) (NTSB, 2018a). Furthermore, the NSTB (2018) also stated that the safety issues presented by the NJT accident and the LIRR accident could be pervasive in other commuter passenger train terminals and intercity passenger train terminals in the U.S.

Table 4. Selected End-of-Track Collisions in the U.S., 2011–2017[1]

Date	Location[2]	Railroad[3]	Speed (mph)	Injury	Fatality	Damage Cost
January 4, 2017	Atlantic Terminal, NY	LIRR	12	112	0	$5,348,864
September 29, 2016	Hoboken Terminal, NJ	NJT	21	156	1	$6,012,000
March 7, 2016	Port Washington Station, NY	LIRR	2	0	0	$1,713,104
June 2, 2015	Hoboken Terminal, NJ	NJT	3	1	0	$23,802

Date	Location[2]	Railroad[3]	Speed (mph)	Injury	Fatality	Damage Cost
January 6, 2014	LaSalle Street Station, IL	NIRC	7	0	0	$25,554
September 23, 2012	Jamaica Station, NY	LIRR	2	2	0	$12,000
February 21, 2012	Port Washington Station, NY	LIRR	3	0	0	$42,334
June 8, 2011	Princeton Station, NY	NJT	16	1	0	$53,500
May 8, 2011	Hoboken Terminal, NJ	PATH	13	35	0	$352,617
March 21, 2011	Port Jefferson Station, NY	LIRR	12	2	0	$110,283
January 27, 2011	New Canaan Station, CT	MNCW	7	0	0	$51,500

Notes:

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

[2] Location: CT: Connecticut; IL: Illinois; NJ: New Jersey; NY: New York.

[3] Railroad: LIRR: Long Island Rail Road; NJT: New Jersey Transit; MNCW: Metro-North Commuter Railroad; NIRC: Northeast Illinois Regional Commuter Railroad; PATH: Port Authority Trans-Hudson.

3.4 FTA of End-of-Track Collisions

FTA is a deductive failure analysis in which a top event is analyzed systematically with Boolean logic to combine a variety of diverse basic events to understand accident sequence chains, identifying safety-critical components, and eventually identifying risk mitigation strategies. Since being conceived by H.A. Watson of Bell Telephone Laboratories (1961), FTA has been used in various railroad safety studies, such as adjacent track accidents on shared-use rail corridors (Lin et al., 2014), train derailments (Wang et al., 2014), restricted-speed accidents (Zhang et al., 2018), and high-speed railway accidents (Liu et al., 2015). A fault tree employs two basic logic gates: an "AND" gate and an "OR" gate. The "AND" gate is used when all events connected by the gate must co-exist if the upper-level event is to be triggered. An "OR" gate indicates that the upper event will take place when any event connected by the gate occurs.

For example, the National Transportation Safety Board (2018a) report showed that the engineer's OSA led to fatigue and ultimately to the train operation failure. Thus, two basic events, operations at the stub-end terminal and the crewmember's sleep disorder, were connected with an "AND" gate in the fault tree. The simultaneous occurrence of two basic events contributed to the occurrence of the NJT train collision at Hoboken Terminal.

Based on historical accidents and engineering experience, a more comprehensive FTA of end-of-track collisions is in Figure 10. Two intermediate events, train operations at stub-end terminals and a failure to stop before the end-of-tracks, must simultaneously occur to result in end-of-track collisions at terminals. The failure to stop before the end-of-tracks can be broken down into three major groups: equipment failures, human factors, and environmental factors. Brake failure is one case of equipment failure and can cause the failure of a train stopping before reaching the end of tracks. Low visibility due to adverse weather conditions (e.g., dense fog, snow) and low adhesion due to vegetation or extreme environmental conditions (e.g., ice) are among environmental factors that affect braking distance. These environmental factors may not affect underground terminals, but would have some influence on outdoor terminals or those covered by rail sheds. In terms of human errors, crewmembers' physical condition problems (e.g., use of alcohol, sleep deprivation, deteriorating vision) and inattentive behaviors (e.g., texting) are likely to result in the violation of operating rules and may cause accidents.

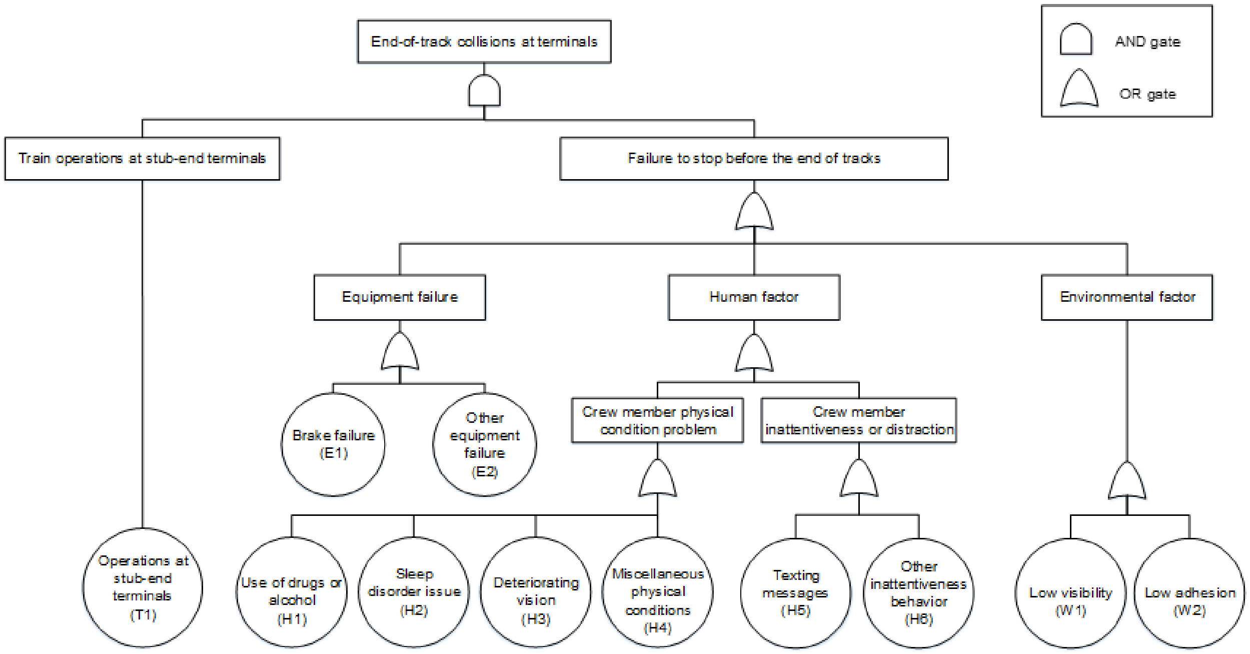


Figure 9. FTA for End-of-Track Collisions at Terminals

Among the selected end-of-track collisions from 2011 to 2017 (Table 4), only the one in LaSalle Street Station, Illinois, was caused by low adhesion in extreme cold weather conditions. Therefore, two basic events, namely T1 and W2, simultaneously contributed to the collision with the bumping post. The other end-of-track collisions were all caused by human errors. For example, according to the REA database, a sleep disorder issue (H2) was one probable contributing factor for the LIRR accidents in 2011 and 2017, the NJT accident in 2016, and the Metro-North Commuter Railroad (MNCW) accident in 2011. Therefore, advanced technologies or mechanisms to mitigate human errors in the train operations at terminals are important for preventing end-of-track collisions.

4. Micro-Level Analysis with Systems-Theoretic Accident Modeling and Processes (STAMP) Model

4.1 Introduction of STAMP Model

Over the past decade, several end-of-track collisions have occurred, including collisions at Hoboken Terminal on September 29, 2016, and Atlantic Terminal in Brooklyn, New York, on January 4, 2017. Each of these accidents resulted in over 100 casualties, prompting concerns from both the public and the rail industry. The National Transportation Safety Board (NTSB) (2018a) highlighted that safety issues identified from these accidents could potentially exist at intercity and commuter passenger train terminals across the U.S. Previous research on end-of-track collisions at passenger stations is relatively limited. This research uses a system-based, micro-level risk analysis to investigate end-of-track collisions at U.S. passenger stations.

To achieve an explicit understanding of end-of-track collisions and eventually improve the passenger station safety, STAMP was employed with reference information from accident investigation results (NTSB, 2018a; NTSB, 2018b; NTSB, 2018c) (FRA, 2018). STAMP envisions safety as a control problem that is embedded in an adaptive socio-technical system and accidents are caused by inadequate control or a violation of safety-related constraints due to component failures, external disturbances, or dysfunctional interactions among system components (e.g., human factors, physical system, environment) (Leveson, 2003; 2004). This accident model has widely been employed in diverse domains, including the rail (Ouyang et al., 2010; Song et al., 2012; Underwood and Waterson, 2014), aircraft and spacecraft (Ishimatsu et al., 2014; Allison et al., 2017), and gas industries (Altabbakh et al., 2014) and can contribute to a safer system to prevent accidents effectively (Leveson, 2003). The STAMP-based analytical results in this section provided an explicit safety analysis of physical components, human error, environmental factors, as well as their interrelationship in the complex terminal operating system. It uncovered the inadequate safety constraints at each hierarchical level from end-of-track collisions and contributes to the establishment of safety recommendations and suggestions. In addition, STAMP can also be a practical investigation methodology for government accident investigators, railway practitioners, and academic researchers, as the first system-based study of the U.S. railroad industry. Although previous researchers have conducted STAMP-based studies on railways in China (Ouyang et al., 2010; Song et al., 2012) and the U.K. (Underwood and Waterson, 2014), different countries would have different hierarchical levels proscribed by legislatures, Federal agencies, or train crewmembers. For example, different U.S. railroads may have different operational characteristics, while Chinese railways are managed and controlled primarily by the government on a consolidated basis (Beck et al., 2013).

4.2 Relevant Literature with Respect to Accident Models

Appropriate accident models perform the foundation of accident investigation and prevention strategies. The common accident analysis methods can be classified into several major categories, including but not limited to 1) the Swiss Cheese Model (SCM) and SCM-based models; 2) sequential models; and 3) systematic models. SCM was developed by Reason (1990) and proposed that adverse events result from a series of contributing flaws (e.g., the holes in cheese slices) that must be aligned. The Human Factors Analysis and Classification System (HFACS), the Australian Transport Safety Bureau (ATSB), and EUROCONTROL are universal accident analysis approaches inspired by SCM. Sequential models include FTA, Event Tree Analysis (ETA), and Failure Mode and Effect Analysis (FMEA), most of which are classic techniques for reliability engineering over the past few decades. Moreover, AcciMap, the Functional Resonance Accident Model (FRAM), the Driver Reliability and Error Analysis Model (DREAM), and STAMP are prevailing systematic models. Selected accident models from these three major categories are extensively studied in prior literature (Table 5).

Table 5. Selected Accident Models Used in Diverse Literatures

Accident		References
SCM-based models	HFACS	Xi et al., 2010; Salmon et al., 2012; Chauvin et al., 2013; Madigan, et al., 2016
	ATSB	ATSB, 2008; Underwood and Waterson, 2014
	EUROCONTROL	Reason et al., 2006; Roelen et al., 2011
Sequential models	FTA & ETA	Doytchev and Szwillus, 2009; Ramaiah and Gokhale, 2011; Chi et al., 2014
	FMEA	Zeng et al., 2010; Ramaiah and Gokhale, 2011
Systematic models	AcciMap	Rasmussen, 1997; Branford et al., 2009; Salmon et al., 2012; Salmon et al., 2013; Underwood and Waterson, 2014
	DREAM	Hollnagel, 1998; Warner and Sandin, 2010
	FRAM	Hollnagel, 2012; Patriarca et al., 2017
	STAMP	Leveson et al., 2003; Leveson, 2004; Ferjencik, 2011; Salmon et al., 2012; Allison et al., 2017; Underwood and Waterson, 2014

In comparison with SCM-based models and sequential models, systematic models perform better in accidents from complex systems, such as a rail system (Ouyang et al., 2010; Song et al., 2012; Underwood and Waterson, 2014) and aviation (Ishimatsu et al., 2014; Allison et al., 2017). Previous researchers (Leveson, 2012; Hollnagel, 2012) who have drawn some criticisms on the SCM-based models pointed out that SCM-based models oversimplify accident causation through a linear chain of events. In complex systems, non-linear interactions among environmental factors, human errors, organizational factors, and mechanical failures may get involved and cannot be described comprehensively using these traditional models. However, systematic models, such as AcciMap and STAMP, have been developed to overcome these limitations of complex relationships and provide an explicit understanding of sophisticated accident causations. Ferjencik (2011) pointed out that systematic models can offer deeper judgment and insight into the hazards and risks from dynamic processes and complex systems. Sequential models also have the similar weakness compared to systematic models (Al-shanini et al., 2014). Although there are many conjunctive conditions and contributors in some adverse events, sequential models typically describe accidents as certain combinations of failures or events. Al-shanini et al. (2014) argued that sequential models cannot represent multi-liner causes or nonlinear causes in accidents. Therefore, systematic models are applicable in the analysis of the end-of-track collisions at passenger stations, as a system involving multiple system components with complicated interactions.

While there is no direct comparison between STAMP and all other non-STAMP systematic models, Underwood and Waterson (2014) compared STAMP against AcciMap and concluded that STAMP provides more explicit descriptions of system structure, component relationships, and system behavior, and that STAMP may be a more appropriate option for researchers with some features, such as greater thoroughness and taxonomy. With these features, in the domain of rail safety and train accident study, Ouyang et al. (2010) and Underwood and Waterson (2014) have implemented a STAMP-based analysis on the Jiaoji railway accident in China and the Grayigg train derailment in the U.K., respectively. As a systemic accident analysis method that can embody the concepts of systems theory, STAMP was selected in this section to study end-of-track collisions at passenger stations in the U.S. The rail safety operation constraints, hierarchical levels of control, and process models of the STAMP model developed in this section can also be adapted to study other train accidents in the U.S. railway system.

4.3 Structure of STAMP-Based Accident Analysis

In STAMP models, safety (e.g., train operation safety at stub-end passenger stations) is viewed as a control problem. Leveson (2003) summarized that accidents take place due to inadequate enforcement of safety-related constraints on the development, design, and operation of the system, instead of a series of failure events. Three basic concepts in STAMP, hierarchical levels of control, constraints, and process models, are briefly introduced in this section.

In systems theory, systems are viewed as hierarchical structures, in which each hierarchical level imposes constraints on the activity of the level below it. Constraints or lack of constraints at a certain level would control or permit lower-level behavior (Checkland, 1981). The behavior includes the engineering design, the physical component, management, human factor, and regulatory behavior. Components that violate the system safety-related constraints or their interactions are likely to result in accidents. Taking train operation in the U.S. as an example, a hierarchical socio-technical control structure combines five socio-technical system levels: the U.S. Congress, government agencies (e.g., FRA, NTSB), industry associations (e.g., American Public Transportation Association, Association of American Railroads), railroad companies, and operating process that involves train crewmembers and train movements, from top to bottom, in general.

Apart from constraints and hierarchical levels of control, a process model is also a basic STAMP concept. Figure 11 shows a basic process control loop where a human controller (e.g., train engineer) takes charge of train operation. In essence, there are two common controllers in a model of the controlled system, the human controller and the automated controller. Based on commonly employed train operation methods in the U.S., train movements are primarily controlled and managed by human controllers and are also supervised by a train protection controller, such as Positive Train Control (PTC). PTC is a train control system capable of reliably and functionally preventing train accidents attributable to human error, by slowing or stopping trains automatically. The PTC system is not a completely automated controller. Instead, it functions and takes charge of train operation only if the human controller (e.g., train engineer) fails to or inadequately controls train safely and properly, although PTC keeps monitoring the performance of engineers and train movements. Therefore, in Figure 11, the interconnection between the train control system and the actuator (commands applied by train control system to actuator) is marked with a dashed line, and is not always active. Furthermore, since RSIA08, nationwide implementation of PTC has been underway in the U.S. Railroads servicing toxic- or poisonous-by-inhalation hazardous materials and railroads that provide regular intercity or commuter rail passenger transportation are required to implement PTC systems by December 31, 2018, with the opportunity for an additional 2 years upon approval from FRA (FRA, 2011a). It means that currently US railroads are in the process of deploying and implementing PTC systems, such as Interoperable Electronic Train Management System (I-ETMS) used by Class I freight railroads and the Advanced Civil Speed Enforcement System (ACSES) used by Amtrak on the Northeast Corridor (NEC). Furthermore, the concepts of several terms (e.g., sensor, actuator, disturbance, process input, and process output) in the process model are also interpreted with explanatory descriptions and common examples in Table 6.

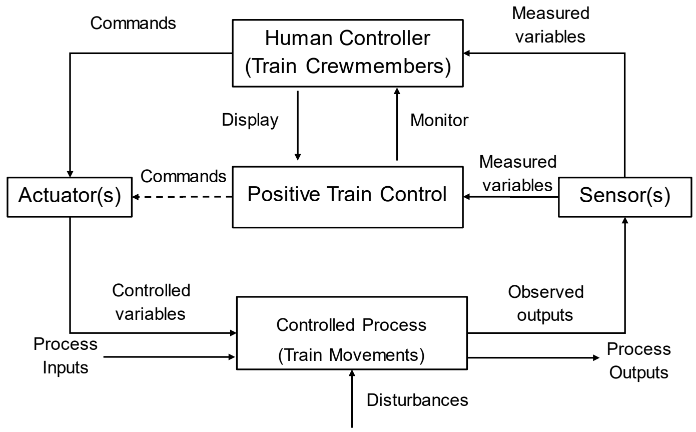


Figure 10. A Basic Process Model in Train Operation at U.S. Passenger Stations

Table 6. Explanatory Descriptions of Terms in STAMP Process Model

Terms	Explanatory Descriptions	Examples
Sensor(s)	Onboard and wayside devices to provide necessary measured variables	Cab signal, speedometer, WIU, etc.
Actuator(s)	Devices to transmit control commands and control the train movements	Throttle, brake system, etc.
Disturbances	External environments that could have an effect on train movements	Snow, extreme wind, flood, ice, etc.
Process Inputs	Input information and devices that support/influence the train movements	Signal, track condition, rolling stock condition, safety equipment (e.g., bumping post), etc.
Process Outputs	Output information and conditions that result from train movements	Vibration, noise, severe hazard (e.g., derailment, collision), etc.

4.4 STAMP Model of End-of-Track Collisions at Passenger Stations

This section applies the STAMP model to study end-of-track collisions with a potential high consequence at passenger stations. Figure 12 shows the general safety control structure of train operations and major safety-related requirements at passenger stations. The general system hazard related to train operations at the stub-end passenger terminals is the failure of the train to stop at the end of the terminating track and to collide with the bumping post. This hazard should be prevented with system safety constraints, as shown in Figure 12. These general constraints must be enforced by the entire socio-technical control structure at passenger stations to achieve a positive stop before reaching bumping posts. In other words, an end-of-track collision at passenger stations results from either a lack of or the inadequate enforcement of the constraints at a certain hierarchical level.

Numerous Federal agencies and rail industry associations are related with train operation safety in the U.S.; this study only considered those that had a close relationship with train operations at passenger stations. Furthermore, effective communication channels between the hierarchical levels are essential (Figure 12). For example, in the communication channels between Congress and FRA, Congress establishes and enacts legislation as well as grants budgets to FRA. In return, FRA needs to submit government reports so Congress can attain information on proposed legislation, oversee the activities of the government agency, and evaluate the implementation of Federal laws (GPO, 2018). In terms of the connections between FRA and the railroads, FRA has the responsibility for making regulations and certifications for the railroad industry, as well as the supervision of railroads' execution. The rules and regulations are published in the form of Federal Register and the CFR. Some safety recommendations and standards are also published by FRA, such as a safety advisory to remind railroads of the significance of compliance with restricted speed operating rules (FRA, 2012), an updated passenger equipment safety standard for high-speed trains that can travel up to 220 mph (FRA, 2016a). Conversely, railroads must work out necessary accident/incident reports, implementation plans, and operations reports. Current regulations (FRA, 2011a) designate train operations at passenger stations as a regulatory exemption from the PTC requirement, a topic that will be discussed in the following sections.

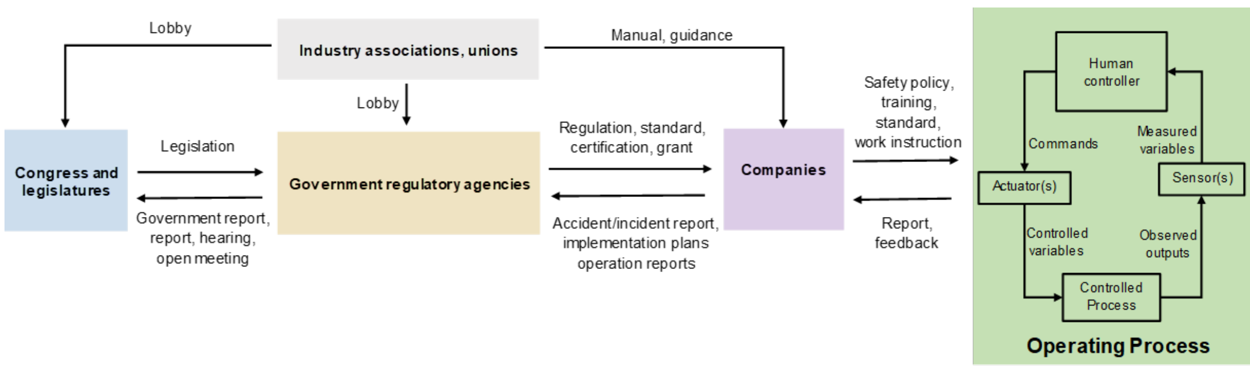


Figure 11. Basic Train Operation Control Structure at Passenger Stations

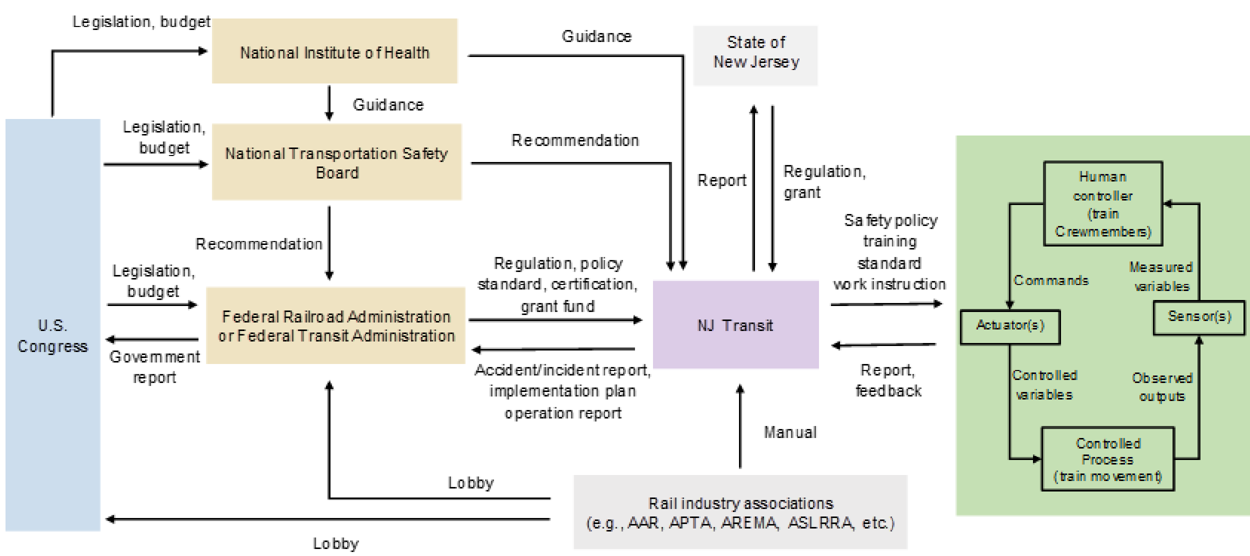


Figure 12. Basic Safety Control Structure of 2016 NJT Hoboken Accident

4.5 Case Study in NJT Accident at Hoboken Terminal

4.5.1 Accident Narratives

The accident information and likely causes referenced in this section primarily stem from NTSB accident investigation reports (NTSB, 2018a; 2018b; 2018c) and the FRA database (FRA, 2018a). This section provides a concise summary of essential accident details to underpin the analysis of end-of-track collisions at passenger stations using the STAMP model.

At Hoboken Terminal, a collision occurred on September 29, 2016, around 8:38 A.M. (Eastern Standard Time). An NJT train failed to stop before reaching the end of track 5, ultimately overriding a bumping post—a rigid structure level with the train's coupler at the track's end—before colliding with the terminal wall (Figure 14).

Figure 13. Map of Hoboken Terminal Tracks

According to the locomotive event recorder data released by NTSB (2018b), the train was traveling about 8 mph at about 38 seconds before the collision, and the throttle position went from idle to number 4. As a result, the train speed started to increase and reached about 21 mph. Just under 1 second before the collision occurred, the engineer applied the emergency brake, yet the train speed at the time of the collision was still documented as 21 mph in the locomotive event recorder. The accident train included 1 cab car, 3 passenger cars, and 1 locomotive at the rear with about 250 passengers and 3 crewmembers (i.e., engineer, conductor, and assistant conductor). In total, 110 people were injured, and 1 person on the passenger platform was killed by flying debris (NTSB, 2018b). The total damage to the equipment, track, signal, and structure damage was over $6 million (FRA, 2018a).

4.5.2 STAMP-Based Analysis in NJT Accident at Hoboken Terminal

As an end-of-track collision at Hoboken Terminal, the accident had roughly the same operation safety control structure as depicted in Figure 12. The general system hazard related to the NJT accident is identified as a failure to stop at the end of the terminating track where it struck the bumping post. The constraints associated to this hazard are applied by the entire socio-technical control structure to enforce safe train operations at passenger stations. The subsequent analysis of the control structure is shown in Figure 13. Further discussions took place to understand the occurrence of the NJT accident and to analyze its inadequate control actions in this complex train operation system at the passenger station. A detailed analysis of inadequate enforcement occurred with the selected system components' safety constraints, failures or inadequate control actions, and supportive backgrounds, as shown in Figure 13.

4.5.2.1 FRA

FRA has primary responsibility for developing and promulgating legislation, regulations, and policies. Three CFRs, 49 CFR Part 238, 49 CFR Part 229, and 49 CFR Part 236, involve direct applications of rail operations at passenger stations (e.g., Hoboken Terminal). In 49 CFR Part 238, both locomotive and passenger car equipment are required to be inspected and maintained periodically. Per the requirements from 49 CFR Part 229, an alerter, as a safety device in the locomotive cab, is used to monitor engineer-induced control activities and promote engineer attentiveness. If the system detects no control activity from the engineer in a predetermined time, both audible and visual alarms are activated to prompt a response. In addition, 49 CFR Part 236 defines the terminal track as the MTEA, in which train operations are limited to restricted speed. According to the railroad accident brief investigated by NTSB (2018b), these three published FRA regulations and policies were strictly followed by NJT. More specifically, in the mechanical part, the inspection and maintenance program of NJT met the requirements in 49 CFR Part 238. Before the trip, the controlling cab car and air brake received a comprehensive inspection per FRA requirement. In addition, the alerter was installed in the locomotive cab and was operating properly, as required by 49 CFR Part 229. The signals indicating restricted-speed operation as well other wayside signals were inspected and verified for proper performance, and there were no deficiencies in the in-cab signal code rate. NTSB (2018b) concluded that both signal system and train control system were functioning as designed and were in accordance with the FRA requirements. Meanwhile, NTSB (2018b) pointed out that there was a lack of legislative rules or non-legislative recommendations regarding medical standards or regulations to address OSA screening and treatment.

According to NTSB (2018a), OSA was a contributing factor in the NJT accident and several previous train accidents. In train operations, OSA can result in frequent interruptions in sleep and leads to expanded fatigue and daytime microsleeps. Since 2010, NTSB (2018a) has investigated 6 OSA-related railroad accidents, which caused 9 fatalities and 283 injuries in total; the agency identified sleep disorders as a key medical fitness issue for train employees. As a result, a variety of safety recommendations were subsequently made to FRA, including NTSB (2012) and NTSB (2016). These safety recommendations encouraged FRA to develop and enforce standards to medically screen railroad employees for sleep apnea and other sleep disorders. However, according to NTSB (2018a), it was still in the process of responding to the reiterated safety recommendations, and there were no medical standards or regulations that directly addressed OSA screening and treatment mandated by FRA at the time of the NJT accident.

Advanced Civil Speed Enforcement System II (ACSES II) is one type of PTC system approved and certified by FRA. ACSES II was implemented by NJT to prevent human-error-related train accidents through slowing or stopping trains automatically. However, train operations at passenger stations are designated as a regulatory exemption from the PTC requirement based on current FRA regulations (FRA, 2011a). Thus, stopping a train on a terminating track would depend on the attentiveness and compliant behavior of the engineer.

4.5.2.2 NJ Transit

NJT is responsible to follow safety requirements and constraints strictly to mitigate operational risks. Per FRA requirements, it must ensure that mechanical components work without defects and maintain an inspection and maintenance program for locomotives and passenger cars. Moreover, training and physical examination for crewmembers are also essential. NJT is responsible for continuing education requirements for train crewmembers to maintain competence and knowledge about rail safety. NJT must provide periodic physical examinations to ensure that those in safety-sensitive positions are fit for duty. Furthermore, according to NTSB (2018a) and (2018b), the system safety program plan (SSPP) and OSA screening are two safety constraints that involve inadequate control actions and were identified by NTSB as the probable contributing factors to the NJT accident at Hoboken Terminal (Figure 15).

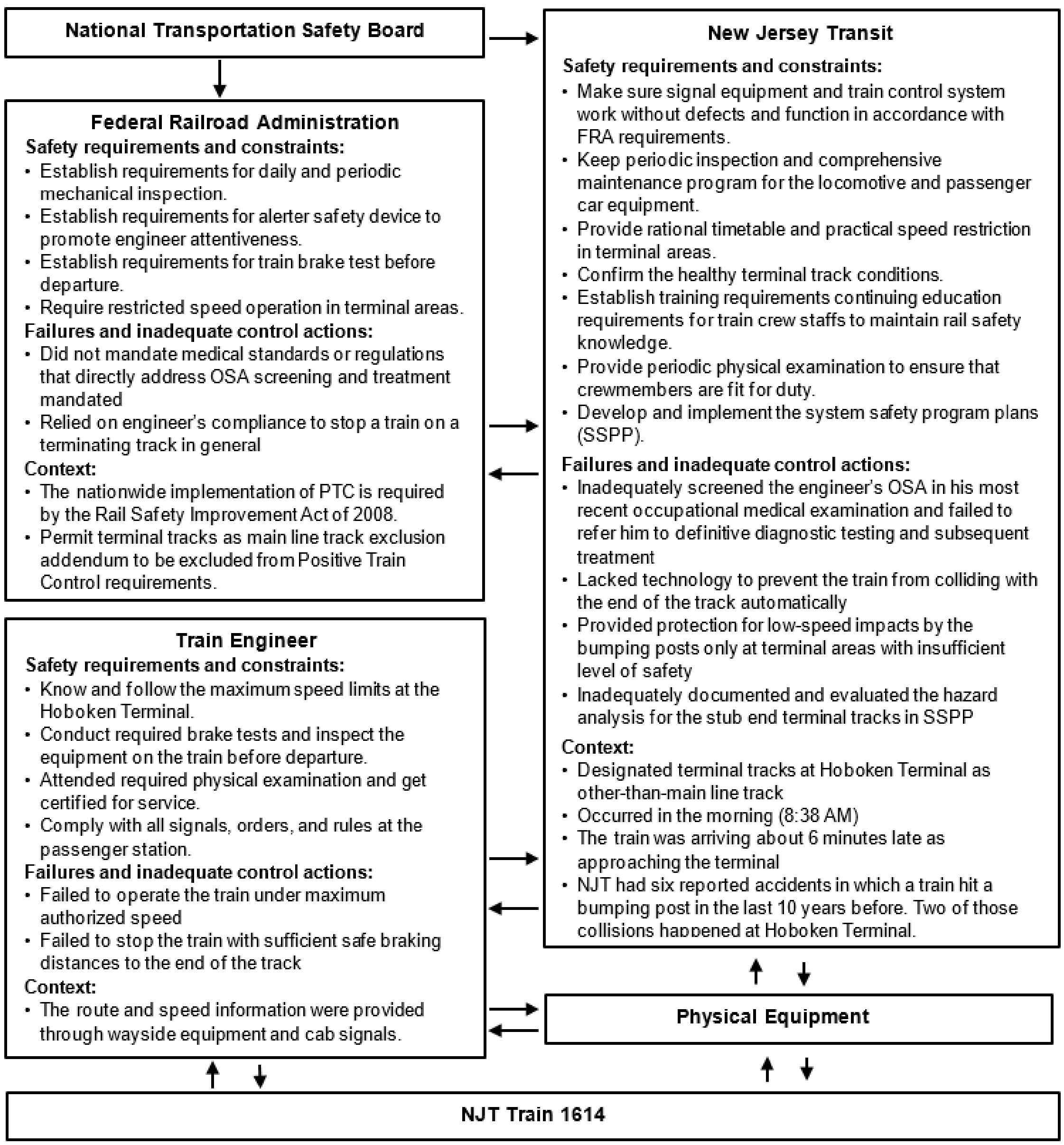


Figure 14. STAMP Analysis of Control Structure and System Components with Inadequate Constraints (Based on NTSB Reports)

SSPP assists monitoring operations and collecting appropriate data to identify emerging safety issues before accidents occur, in which the significance of hazard management was recognized both by FRA and APTA (NTSB, 2018a). APTA (2006) identified SSPP as the first element of a formal process for applying the principles of system safety. This is described as a structured program with proactive processes and procedures to identify and eliminate hazards and the resulting risk to the railroad's system. The Manual for the Development of System Safety Program Plans for Commuter Railroads identifies 23 elements for commuter railroads to consider in the development of an SSPP (APTA, 2006). Based on NTSB (2018a), although NJT has its SSPP in effect at the time of the accident, it lacks identification and evaluation of the potential for a collision between a train entering a stub-end track and the bumping post.

In terms of OSA screening, although there were no medical standards or regulations mandated by FRA at the time of the accident, NJT had a physical screening process related to OSA and other sleep disorders in effect. However, according to NTSB, the engineer's medical provider failed to complete the form and follow the procedures that would have detected his risk factors as OSA. As a result, the sleep-apnea-related risk from safety-sensitive accident train engineer was not adequately screened and identified. Then it failed to refer him for definitive diagnostic testing and treatment (NTSB, 2018a). In addition, NJT designated terminal tracks at Hoboken Terminal as other-than-mainline tracks and exempted them from PTC requirements, in accordance with FRA (2011a). With this context, train operation at Hoboken Terminal largely relied on a train engineer who had severe OSA that was not diagnosed and treated.

4.5.2.3 Train Engineer

The train engineer had the responsibility to make sure the train follows all signals, rules, and regulations at Hoboken Terminal. Some additional safety requirements were also followed by the train engineer, including the inspection of train equipment and locomotive cabs before departure. Train engineers should receive and transmit information via radio or telephone to the conductors and dispatchers and should also be aware of the surrounding areas and necessary decision making accordingly. Nonetheless, the engineer in this accident failed to follow the speed limits and restricting signal. As a result, the train speed was reduced, but the insufficient braking distances to the end of the track led to the accident. The engineer's increased fatigue due to frequent sleep interruptions contributed to failing to stop the train after entering Hoboken Terminal.

As another recent high-consequence end-of-track accident at the passenger station, the LIRR accident at Atlantic Terminal on January 4, 2017, were similarly inadequate comparing against the NJT accident at Hoboken Terminal based on investigation results from NTSB (2018a). Additional accident details and investigation results are also available in NTSB reports (NTSB, 2018a; 2018c).

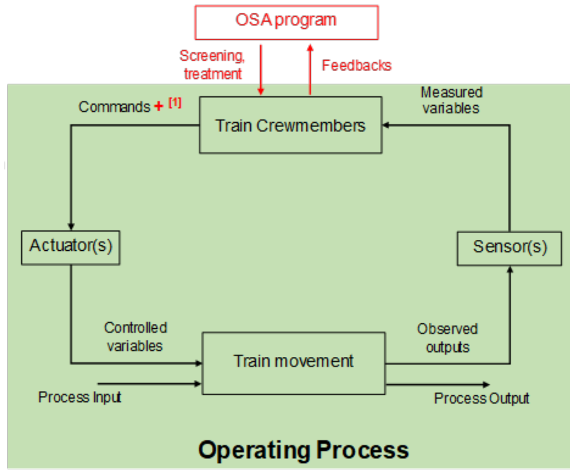
4.6 Discussions of Policy Implications and Practices

The end-of-track collision at Hoboken Terminal demonstrates the potentially severe consequences of passenger station accidents. A STAMP-based analysis of this accident contributes to a distinct understanding of the system hazards, constraints, and hierarchical control structure of train operations at passenger stations. Based on the analytical results, in particular with the inadequate control constraints, this section explains effective safety strategies to reduce accident risks at passenger stations and promote safety. The following subsections discuss the findings based on both STAMP-based analysis of end-of-track collisions and reference information in NTSB (2018a), including (1) OSA screening and treatment; (2) mechanisms to prevent end-of-track collisions automatically; (3) comprehensive SSPP; and (4) bumping posts with higher impact tolerance.

4.6.1 Obstructive Sleep Apnea

OSA is one major contributing factor to fragmented sleep and subsequent daytime fatigue sleepiness, which could be a crucial increasing risk for train crewmembers. In a study of train engineers in Greece, Nena et al. (2008) concluded that OSA was common among Greek railway drivers and 62 percent of train engineers encountered this sleep-disorder issue, while the percentage of adults having OSA in the general population from Western countries was only around 5 percent (Young, et al., 2002). Similarly, Koyama et al. (2012) studied the prevalence of OSA among Brazilian railroad workers. Based on a survey from 745 railroad workers, the prevalence of OSA was approximately 35 percent – higher than the general population. Without OSA screening and diagnosis programs required by Federal agencies or railroads, a relatively high prevalence of OSA would possibly increase the risk of end-of-track collisions at passenger stations. According to NTSB (2018a), the engineer in the NJT accident went through a post-accident study and was diagnosed with severe OSA, which was a probable cause of this accident. Nevertheless, at the time of the collision, there were no regulatory guidelines or recommendations referring to effective diagnosis and follow-up medical treatment in respect to OSA. This STAMP-based accident analysis demonstrates the necessity for government agencies, railroad associations, and railroad companies to work closely to promote the development and enforcement of a complete, effective program involving OSA screening and follow-up medical treatment. To achieve this, extensive research studies could contribute to the development of an effective OSA program. Romero-Corral et al. (2010) disclosed the interactions between body weight (measured by BMI) and OSA, which was also studied in the NJT accident (NTSB, 2018b; 2018c). Epstein et al. (2009) provided a comprehensive clinical guideline for the evaluation and treatment of OSA. An OSA diagnostic was suggested to involve 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). A comprehensive and valid OSA program can be developed to mitigate the risk of OSA to both intercity passenger trains and commuter trains. An intervention policy, inclusive of regulatory guidelines and recommendations pertaining to diagnosis and subsequent medical treatment, is crucial in detecting OSA and other sleep disorders among train crewmembers. In such instances, railroad employees in safety-sensitive positions must meet specified medical standards to ensure their fitness for duty.

Figure 16 offers a visualized interpretation of the operational process involving OSA. Specifically, it suggests the development of an OSA program integrating screening and treatment, guided by the National Institutes of Health. Such a program would be valid for ensuring the fitness for duty of train crewmembers.



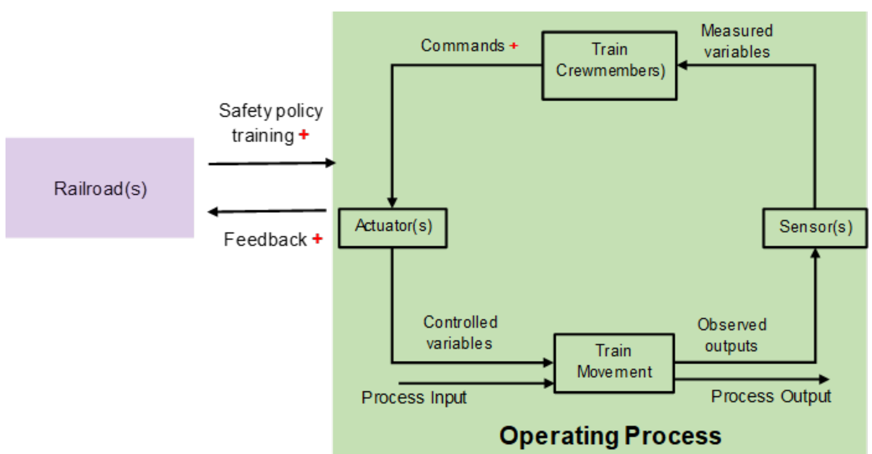
Note: The plus signs (+) represent the reinforcing channels between components. Specifically, train engineers under the OSA program are expected to make more compliant commands and guaranteed safe train movement.

Figure 15. Proposed OSA Program in Simplified STAMP Model

4.6.2 System Safety Program Plans

NJT had SSPPs with rich hazard management to monitor train operations and collect considerable data to identify emerging safety issues. Although six collisions have also occurred between NJT trains and bumping posts between 2007 and 2016—two of them at Hoboken Terminal). NTSB (2018a) pointed out that NJT did not recognize the risk of an end-of-track collision at passenger stations as a key risk factor in SSPP. Similarly, the SSPP overlooked the need for OSA screening and treatment to prevent potential hazards and did not account for undiagnosed or untreated OSA. Therefore, SSPP should be promoted and updated to account for the increased risk of OSA and operational hazards associated with end-of-track collisions. Eventually, a robust SSPP that documents comprehensive hazards can contribute to the mitigation of emerging, critical risk elements through an effective management system.

In Figure 17, the proposed robust SSPP is interpreted visually using simplified STAMP.



Note: The plus signs (+) represent the reinforcing channels between system components.

Figure 16. Proposed Comprehensive SSPP in Simplified STAMP Model

In addition to adding end-of-track collisions and OSA into the SSPP, Federal agencies (e.g., FRA or FTA), industry associations (e.g., APTA), and railroads can construct a reliable SSPP with comprehensive hazards documented. This action would promote safe train operations (commands in Figure 17) by train crewmembers. Moreover, the reports and feedback from train operation process can also advance an exhaustive, continuous safety management system and eventually mitigate the risk at passenger stations before an accident occurs.

4.6.3 Bumping Post with More Impact Tolerance

In the NJT accident, the bumping post (example shown in Figure 18a) located at the end of the tracks was overridden and destroyed by the accident trains. NTSB (2018a) concluded that the bumping post at the accident location did not adequately provide protection by itself at passenger stations. The fixed bumping posts, of the type employed at Hoboken Terminal, can only offer tolerance and protection for a low-speed impact. In theory, a train transfers enormous kinetic energy to the bumping post in an impact (e.g., end-of-track collision) and can easily exceed the bumper's tolerance. After hitting the bumping post, the accident train struck a terminal wall and caused the death of a person standing on the passenger platform due to the falling debris from Hoboken Terminal.

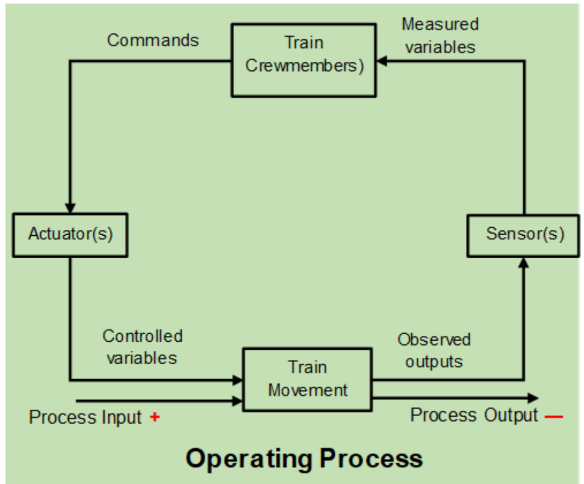
In addition to the fixed bumping post in the NJT accident, energy-absorbing bumping posts (Figure 18b) are dynamic barriers that utilize friction mechanisms and hydraulic systems and can absorb relatively higher-speed impact. However, NTSB (2018a) pointed out that most terminals do not have the physical space for this type of bumping post for the friction mechanisms and the extensive distances they demand. Moreover, Moturu and Utterback (2018) identified that energy-absorbing bumping posts are still limited in the amount of kinetic energy that they can tolerate and would have large likelihood to fail at speeds over 10 mph. It means even if this type of bumping post had been in place, it still could not bear the impact of the 21-mph NJT train. Therefore, it is essential to design and implement bumping posts with both higher impact tolerance and more practical function in complex station areas.

(a) Fixed bumping post

(b) Energy absorbing bumping post

Figure 17. Bumping Post Examples: a) Fixed Bumping Post; b) Energy Absorbing Bumping Post (Cortez, 2016)

Figure 19 indicates how advanced bumping posts increase the level of safe train operations at passenger stations. Advanced bumping posts located at the end of terminating track can strengthen the impact tolerance to the uncompliant train movements. As a result, the potential collision consequence (process output in Figure 19) under a reinforcing collision protection device would be reduced.



Note: Plus signs (+) and minus signs (-) symbolize the reinforcing loops and reduction loops, respectively.

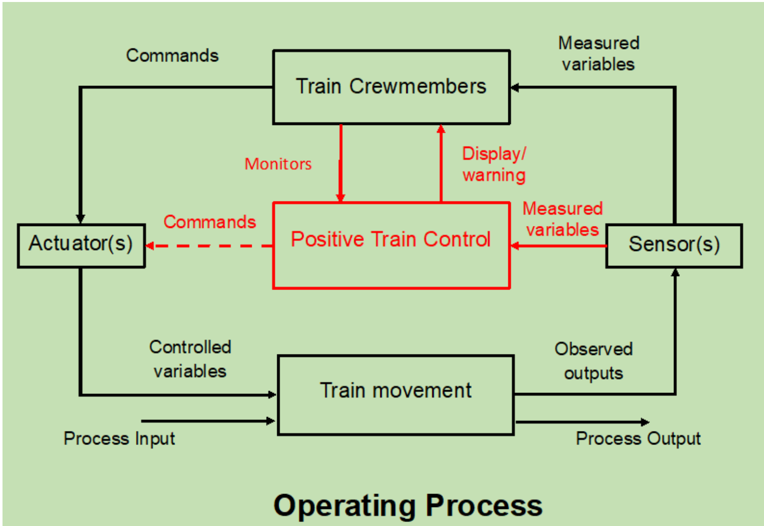
Figure 18. Proposed Bumping Post with More Tolerance in Operating Process of STAMP Model

However, there is always an upper limit of allowed impact speed for this impact-absorbing device. In practice, a bumping post should be coupled with end-of-track collision risk mitigation strategies (e.g., OSA screening program, train protection systems, comprehensive SSPP) to effectively prevent end-of-track collisions throughout the rail system.

4.6.4 Collision Avoidance and Mitigation with PTC Systems

NJT designated the terminating tracks as "other-than-mainline track" and exempted them from PTC implementation requirements in accordance with Federal regulation (FRA, 2011a). Without the implementation of a PTC system, safe train operations would generally depend on crewmembers' compliant behavior when entering passenger stations with stub-end tracks. However, NTSB (2018a) argued that it cannot provide the level of safety necessary to protect the public. In the study of the safe approach of train terminals, Moturu and Utterback (2018) stated that implementation of a design mitigation (e.g., PTC) has distinct benefits for controlling speed entering terminal-point locations. Therefore, it is critical to implement a mechanism that can automatically stop a train before the end of the tracks even if the engineer is negligent or disengaged to mitigate potential hazards to passengers and bystanders at passenger stations.

NJT train operating procedures and train movements during the accidents were managed only by train crewmembers (Figure 20). If the appropriate wayside and cab signal are displayed, the train crewmembers would exhibit compliant behavior. Deviation from received information during operations may lead to hazards or accidents. Implementing a train control system, such as PTC, can effectively prevent train accidents caused by human error. The train movements are still under the control of train engineers but are also monitored by PTC. Taking ACSES, one of the PTC technologies that are primarily used on the NEC and mostly implemented by Amtrak and commuter railroads (e.g., NJT and LIRR), as an example, it integrates the locomotive computer, wayside device, communication network, transponders, and back office to collect and analyze train real-time status, movement authority, and speed restriction information (measured variable from sensors to PTC). If the train crewmembers fail to appropriately operate train movements, ACSES would automatically apply the brakes and bring the train to a positive stop (Zhang et al., 2018).



Notes: Channel between PTC and actuator is marked in a dashed line because PTC controls train movement only if an engineer fails to operate safely. "Commands" in red indicates PTC enforces train movement via physical devices (called an "actuator," such as the brake system, in the diagram).

Figure 19. Process in Train Operation at Passenger Stations a) Without and b) with Collision Avoidance Technology

5. Concept of Operation in Prevention of Restricted-Speed Accidents with PTC

This section examines the potential use of PTC to automatically stop a train before the end of the tracks if the engineer is negligent or disengaged. This research proposed specific modifications and performed a "what-if," scenario-based analysis. This research primarily focused on the enforcement of the two most widely implemented systems, ACSES and I-ETMS, which account for most U.S. PTC systems.

5.1 Current System and Situation

Federal regulations state that the PTC system is not required to perform its functions when a train is traveling under restricted speeds (FRA, 2011a). For example, in both the NJT accident at Hoboken Terminal and the LIRR accident at Atlantic Terminal, trains operating on terminating tracks were excluded from PTC installation. Meanwhile, NTSB (2013) (2018a) (2018b) pointed out that a PTC system would have prevented some restricted-speed accidents if it had been installed and used. Therefore, it is important that the implemented mechanisms can automatically stop a train before the occurrence of such accidents, even if the engineer is negligent or disengaged, to promote the safety of restricted-speed operations. PTC may be a feasible option to achieve this function. A careful evaluation in a separate study will need to take place regarding cost-effectiveness in preventing restricted-speed accidents.

5.1.1 Background, Objectives, and Scope

With the implementation of PTC throughout the U.S., automated enforcement and warning of wayside signals will become a reality. As an overlay system, PTC can only be enforced in situations where all the information is available pertaining to train detection, switch position, etc. There are times and locations when this information may not be known, and the underlying train control system provides indications to the train that it is unable to provide the normal warning and safety checks it would normally perform. In this case, a "Restricting" aspect is displayed on the wayside signal, placing the responsibility of collision avoidance, some route protection and other functions onto the locomotive operator. In these instances, the PTC system may not be able to provide the full enforcement.

This ConOps provides an understanding of the issues related to restricted speed enforcement, and discusses potential options for PTC systems (i.e., I-ETMS and ACSES) to fill the gap of enforcement presented by this issue. This will cover a vast majority of the PTC systems installed in the U.S.

5.1.2 Description of Current Technology

All PTC types are overlays onto the existing train control system. In signaled territory, this means that the legacy infrastructure still carries the main burden of safety for train operations. Meanwhile, PTC enforces wayside signals based on a combination of predetermined data and real-time information from wayside devices (e.g., signals, switches, and defect detectors).

I-ETMS uses Wayside Interface Units (WIU) to communicate the status of each signal so that the onboard computer can enforce the speed associated with the signal aspect. Position data is obtained by a combination of GPS receivers and axle tachometers. Full service and emergency brake applications are applied when speed limits associated with the signal aspect are exceeded.

ACSES type PTC is normally used along with a cab signal system with speed enforcement called Automatic Train Control (ATC). Position determination is achieved by in track transponders and axle tachometers.

5.1.3 Modes of Operation for the Current System

Current PTC systems enforce restricting speed at a maximum speed of 20 mph with no regard for either the range of vision or other key physical features, such as descending grade in advance of the train. In most cases, this can result in trains not being enforced to stop short of an obstruction, switches not being properly lined, etc.

5.1.4 User Classes and Organizational Structure

User classes and their corresponding organizational structures are distinguished by the ways in which users interact with the current system. The typical railroad structure includes systems-level design and management (engineering), division level maintenance forces (communications maintainers, signal maintainers, and supervision), operating personnel (train crews, dispatchers, and superintendents), passengers, contractors (system integrators, installers, operators and supervision), tenants (as defined by FRA for PTC systems) and regulatory agencies (FRA, Public Utilities Commission, and authorities).

5.1.5 Support Environment

Current PTC support involves several Federal and State agencies such as FRA, the Federal Transit Administration (FTA), the Federal Communications Commission (FCC), and State oversight offices. These organizations provide regulatory direction as well as limited funding for PTC construction and maintenance.

Suppliers of equipment and products such as Wabtec, Alstom (2013), Ansaldo STS, and Siemens (2012), as well as the consultant industry provide integration and maintenance support services. PTC is an evolving technology that requires a constant stream of apparatus refreshing and software updates. This will remain the norm for the foreseeable future.

The I-ETMS committee is responsible for system specification and management in terms of operation and development. This is key to the interoperability requirements within the RSIA08, as amended. User groups have been formed for other PTC system types to perform the same or similar functions.

5.2 Technology-Specific Concept of Operations

5.2.1 Concept of Operations with ACSES

In an ACSES system, a set of transponders (two transponders in one set) located right before MTEA (Figure 21a) mark the end of the full ACSES territory at the end of a main track. When the train reaches this point, this set of transponders would inform the onboard ACSES system that it is entering "Out of ACSES Territory" and the ACSES system would go into a dormant state. The ACSES system being deactivated does not enforce any stop or speeds, but the ATC system enforces restricted speed at 20 mph or 15 mph. The ATC system in U.S. railroads integrates with cab signals and involves speed enforcement. With the ATC system, if the train movement violates speed requirements, an audible alarm would be activated. If the alarm is not acknowledged and no brake is applied, a penalty brake application would be made automatically to reduce train speed. Although the maximum authorized speed at terminal tracks can be enforced by the active ATC system, a train moving under that maximum speed could still cause a collision. For example, a train moving at 5 mph can still cause an end-of-track collision, which cannot be prevented by the ATC alone. Thus, a safe positive (absolute) stop before the end of track continues to depend on the engineer's compliant behavior.

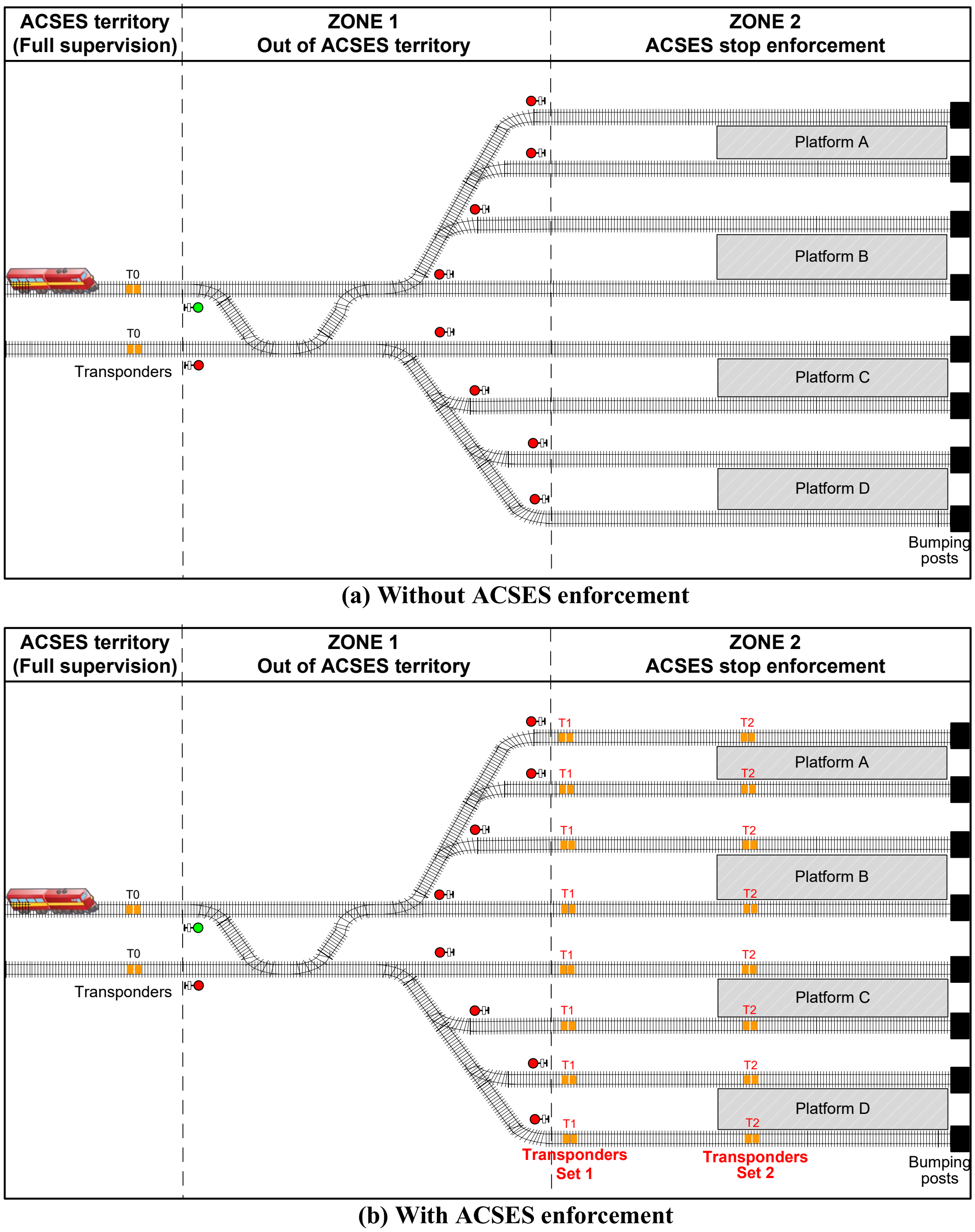


Figure 20. A Simplified Stub-End Terminal a) Without ACSES and b) with ACSES Enforcement

The proposed solution is to divide the terminal area into two zones and install additional transponder sets at the second zone, as shown in Figure 21b. The first transponder set (T1 in Figure 21b) causes the train system to re-enter ACSES territory and provides PTS information, identifying the end of the platform track as the stop target. In addition, it provides linking distance information to the next transponder set (T2). The first transponder set should be located at a distance greater or equal to the braking distance needed to stop the train safely. The second transponder set (T2 in Figure 21b) provides not only a PTS with the distance to the bumping post but also the redundancy to the first set, resulting in better stopping accuracy.

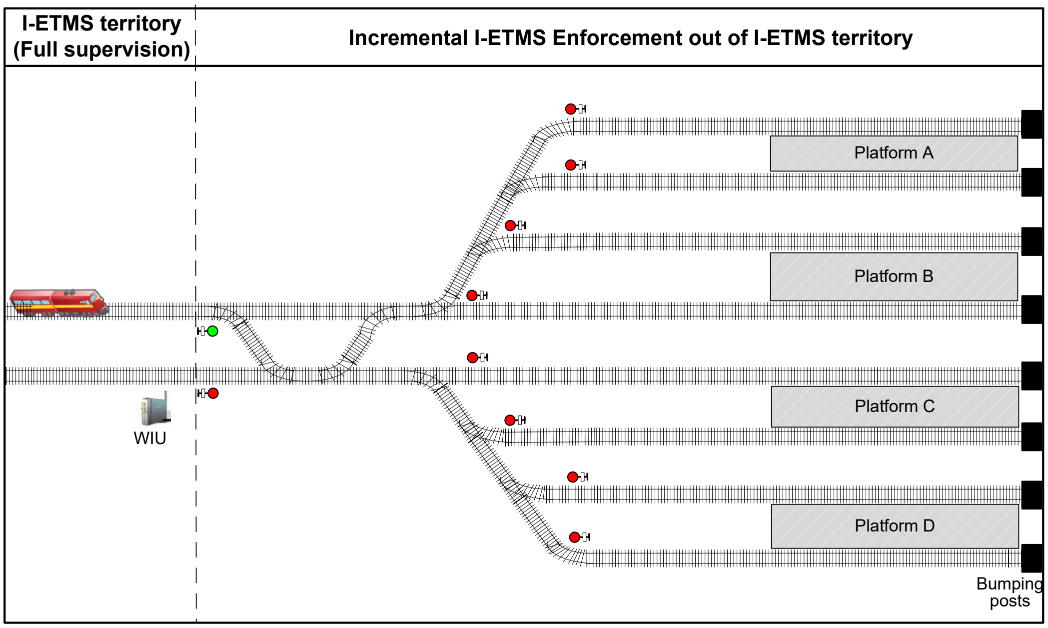
As the train reads the first transponder set T1 in Zone 2, the ACSES system calculates a braking curve based on the real-time train speed and the present distance to the target, such as a bumping post. If the system determines that sufficient braking distance exists at a given moment, the train operation will continue to be commanded by the engineer. If there is insufficient stopping distance, the active ACSES system will release a warning, which, if ignored by the locomotive engineer, would cause the system to slow the train so the train can safely stop short of reaching the end of the terminating track. When the train changes its direction and departs from the terminal, it will read the transponders T2 and T1 in the reverse direction. The message in these transponder sets for this direction will tell the train system that it is leaving ACSES territory until it reaches the location where ACSES territory with full supervision begins (Figure 21b).

5.2.2 ConOps with I-ETMS

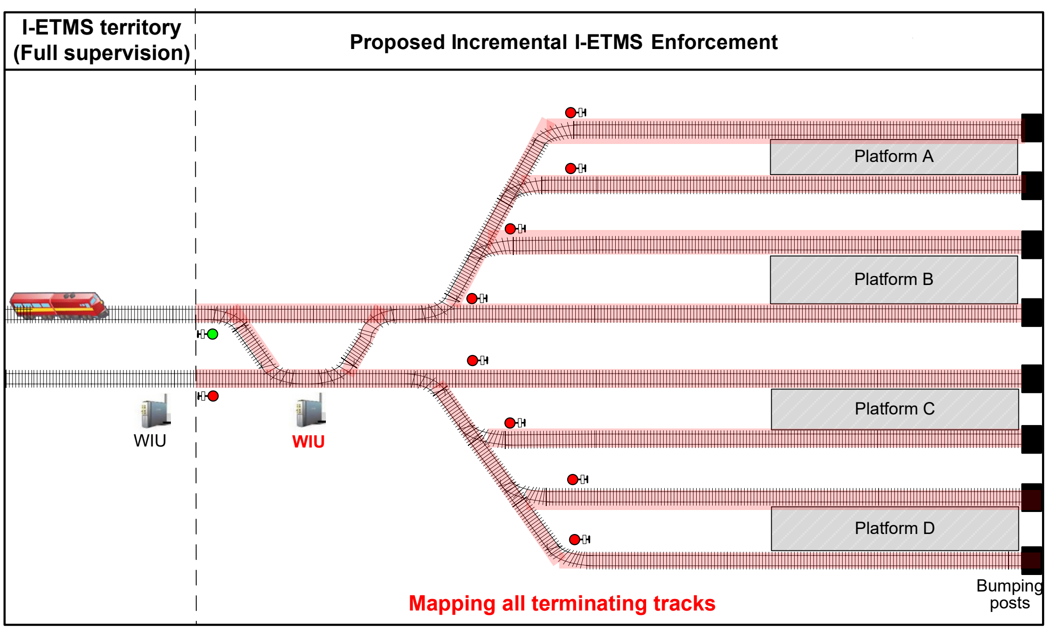
As mentioned in Section 5.1, the I-ETMS system employs GPS navigation to track train movements and real-time location. In practice, many passenger terminals (e.g., Chicago Union Station) are either underground or are surrounded by crowded buildings that make reception of GPS signals difficult or impossible. As a result, it is challenging for the I-ETMS system to enforce a positive stop relying solely on GPS.

The proposed ConOps is to map all the terminating tracks to obtain the distance between a point where the train can obtain a good GPS signal and the end of the track (Figure 22b). The distances from that point to each bumping post need to be measured over every possible route because there can be multiple routes with dissimilar route lengths. When the I-ETMS system loses the GPS signal, the distance that the train has traveled can be continuously measured through counting pulses from wheel sensors, which is known as “dead reckoning.” In addition to the traveled distance, the system should also know the distance to the bumping post. Therefore, it is essential to know the position of every switch to recognize which route the train would take and to determine how far to travel before enforcing a positive stop. To achieve this, a WIU would be required at the terminal to monitor all the switches within the terminal. The onboard system would query the WIU(s) to obtain switch position information via data radio. Having obtained the determined route, the I-ETMS system receives the permissible distance that it can travel before reaching the bumping post. Correspondingly, the I-ETMS can calculate a braking profile based upon real-time train speed and the remaining distance to the stop target, and then a positive stop can be achieved before the end of the track.

The proposed PTC enforcement on terminating tracks may have certain engineering challenges, such as the close proximity of signals and switches in the terminal areas, the complexity of track-work, potential false penalty hits, and the reliability of transponder function for slow train movements. In addition to end-of-track collisions, the prevention of train-to-train collisions in terminals may be a potential research area. If PTC is used to prevent this type of accident, the following train would need to know where the rear end of the lead train is located to calculate a braking profile to enforce a positive stop before hitting the rear end of the lead train. However, the current PTC systems cannot fully achieve these functions. Therefore, future research might explore technologies to locate both the head end and rear end of each train, in support of train-to-train collision prevention. This enhanced positioning technology can also support the development of "moving block" systems.



(a) Without I-ETMS enforcement



(b) With I-ETMS enforcement

Figure 21. A Simplified Stub-End Terminal a) Without I-ETMS and b) with I-ETMS Enforcement

5.3 Discussions of Alternative Restricted-Speed Accident Risk Mitigations

Faced with unchanged restricted-speed accident risk in the last 17 years, it is not only important but crucial to develop and implement safety strategies for restricted-speed train operations. Based on the findings from the FTA and reference information from multiple NTSB investigation reports (NTSB, 2012; 2013; 2018a; 2018b), this section mainly discusses human error prevention strategies (e.g., medical screening and alerter system) and advanced train control system (e.g., 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 section.

5.3.1 Appropriate Medical Program for Safety-Sensitive Personnel

Among the NTSB railroad accident reports that investigated restricted-speed accidents in the last 5 years, the violation of restricted-speed operating rules due to crewmembers' human error has been one primary cause. 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 accident at Hoboken Terminal and the LIRR accident at Atlantic Terminal, the investigation results indicated that both engineers in both restricted-speed accidents were operating trains despite their fatigue due to 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 from 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 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.

5.3.2 Implementation of Alerts

Inattentive behaviors from crewmembers are identified in the fault tree (Figure 10) 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.

6. Benefit-Cost Analysis

6.1 Introduction

PTC implementation at stub-end terminals offers potential safety benefits because it can reduce end-of-track collision risk. Meanwhile, the installation and maintenance of PTC systems are costly and increase capital and operating expense. This section develops a BCA involving estimated safety benefits, incremental costs, net present value (NPV), and the benefit-cost ratios (BCR) associated with PTC implementation at stub-end terminals. The main purpose of this systematic process of identifying and quantifying expected benefits and costs was to help provide decision-makers with economic information and evaluate trade-offs.

The methodological framework on this benefit-cost analysis is based upon Benefit-Cost Analysis Guidance for Rail Projects published by FRA (2016b). The calculations in this report are based on this FRA guidance, railroad experts' experience, and additional reference materials. Specifically, the safety benefits from the prevention of end-of-track collisions are estimated in monetary value by using historical accident data and the estimation approach developed by FRA used in the PTC rulemaking process (AAR, 2017; Peters and Frittelli, 2012; GAO, 2013). The train accident information summarized here is from the REA FRA database. In terms of incremental cost, this research mainly used the unit cost information based upon the collected survey from railroad experts and also involved the proposed ConOps in Section 5.

The analysis accounted for the two most widely used types of PTC systems, ACSES and I-ETMS. The calculations of safety benefits focused on end-of-track collisions only. The sensitivity of the BCR to discount rate, maintenance costs, and the service life was also analyzed.

6.2 General Principles

6.2.1 Analysis Period

FRA (2016) pointed out that the selection of an approximate analysis period is a fundamental consideration in any BCA. Similar to other transportation projects, PTC implementation at stub-end terminals involves initial capital expenditures and maintenance costs that probably bring continuous safety benefits over many years. FRA (2016) recommended that the "the analysis period of a BCA consist of the full construction period of the project, plus at least 20 years after the completion of construction during which the full operational benefits and costs of the project can be reflected in the BCA." In a 2009, the FRA economic analysis of PTC service life was set at 20 years to conduct a 20-year study of the costs and benefits associated with nationwide PTC implementation. As a similar topic related to PTC systems at stub-end terminals only, this study developed a BCA with 20-year projected railroad safety benefits and 20-year costs as the objective variables in total.

Uncertainties remain about how travel markets and patterns may shift in the future–whether the PTC components would be manufactured by the vendors. Therefore, FRA also recommends that "project sponsors generally avoid analysis periods extending beyond 40 years of full operations." (FRA, 2016b)

6.2.2 Converting Nominal Dollars into Constant Dollars

Monetary values for safety benefits and costs are used in the BCA and are measured in dollars. As a study involving a long-term period, it is essential to use constant dollars instead of nominal dollars that do not reflect inflation.

In the study of inflation dynamics, Gali and Gertler (1999) measured inflation with the percent change in the Gross Domestic Product (GDP) deflator. To convert the nominal dollars into constant dollars, the GDP deflator is one general method and has been used in previous studies (FRA, 2009; 2016b). The GDP deflators capture the changes in the value of a dollar over time by considering changes in the prices of all goods and services in the U.S. economy, collected from World Bank data for 2018 (Table 7).

Table 7. 2000–2017 U.S. GDP Deflators Provided by the World Bank (2018)

Year	GDP Deflator	Year	GDP Deflator
2000	80.90	2009	98.79
2001	82.74	2010	100.00
2002	84.01	2011	102.07
2003	85.69	2012	103.95
2004	88.05	2013	105.62
2005	90.88	2014	107.52
2006	93.67	2015	108.69
2007	96.12	2016	110.07
2008	98.05	2017	112.05

This study used a 2017 dollar to estimate the safety benefits and costs in the BCA. The GDP deflator was taken into consideration, and the monetary values (e.g., damage costs) each year was adjusted to 2017 dollars using the GDP inflator (World Bank, 2018).

6.2.3 Discount Rate

The BCA used a discount rate in the calculation of the benefits and costs that occur at different points in time. The discount rate adjusts for the time value of money and allows for safety benefits, as well as the following costs, to be valued in equivalent units. These equivalent units are called present values and are independent when they occur. The time value of money expresses the principle that costs and benefits that occur sooner are more highly valued than those that will occur in the more distant future (FRA, 2016b). The discount rates of 7 and 3 percent per year were employed in FRA (2009) (2016b) and was also employed in this study. The calculation of safety benefits and costs with a discount rate is as follows:

$$PV\_Benefits = \frac{FV\_Benefits}{(1+d)^i} \tag{6-1}$$

$$PV\_Costs = \frac{FV\_Costs}{(1+d)^i} \tag{6-2}$$

Where:

$PV\_Benefits$ and PV_Costs are the present discounted value in constant dollars from year i

$FV\_Benefits$ and FV_Costs are the future discounted value in constant dollars from year i

d = annual discount rate; this study used 3 percent and 7 percent

6.3 Safety Benefits of End-of-Track Collision Prevention

6.3.1 Overview and Accident Data Pool

The primary benefit of PTC implementation at stub-end terminals is the safety benefit or savings expected to accrue from the reduction in the number and severity of casualties arising end-of-track train collisions that would occur on PTC-equipped trains. Business benefits were excluded from the estimations for two reasons. First, FRA (2009) recognized that the general PTC installation in the U.S. has uncertainty and thus has not assumed any business benefits beyond those from railroad accident prevention. Second, the operational impact study indicated that PTC implementation at stub-end terminals had a negligible impact on capacity.

Therefore, in the BCA, the safety benefits related to accident prevention would accrue from a decrease in damage to property such as locomotives, railroad cars, and track, plus environmental damage, track closures, and evacuations. The benefits more difficult to monetize—such as the avoidance of hazardous-material-accident-related costs incurred by Federal, State, and local governments and impacts to local businesses—will also result. These safety benefit categories were considered in the 2009 FRA study of PTC safety benefits (FRA, 2009).

The safety benefits of end-of-track collisions were estimated in monetary value with historical accident data and the estimation approach developed by FRA used in the PTC ruling making process (AAR, 2017; Peters and Frittelli, 2012; GAO, 2013). The train accident information summarized here was from the FRA REA database between 2001–2017. In the database, railroads are required to submit reports of accidents that exceed a monetary threshold for damage and loss (e.g., $10,500 in 2017).

As shown in Table 8, the collisions studied led to 316 casualties (315 injuries and 1 fatality) and over $14,476,832 in damage to infrastructure and rolling stock. In terms of either casualties or damage cost, the most severe accidents associated to Atlantic Terminal and Hoboken Terminal took place in the last 2 years of the study and each led to over 100 casualties and over $5 million in damage costs to rolling stock and infrastructure.

Table 8. End-of-Track Collisions in the U.S., 2001–2017[1]

Date	Location	Railroad[2]	Speed (mph)	Injuries	Fatality	Damage Cost
January 4, 2017	Atlantic Terminal, NY	LIRR	12	112	0	$5,348,864
September 29, 2016	Hoboken Terminal, NJ	NJT	21	156	1	$6,012,000
March 7, 2016	Port Washington Station, NY	LIRR	2	0	0	$1,713,104
June 2, 2015	Hoboken Terminal, NJ	NJT	3	1	0	$23,802
January 6, 2014	LaSalle Street Station, IL	NIRC	7	0	0	$25,554
September 23, 2012	Jamaica Station, NY	LIRR	2	2	0	$12,000
February 21, 2012	Port Washington Station, NY	LIRR	3	0	0	$42,334
June 8, 2011	Princeton Station, NY	NJT	16	1	0	$53,500
May 8, 2011	Hoboken Terminal, NJ	PATH	13	35	0	$352,617
March 21, 2011	Port Jefferson Station, NY	LIRR	12	2	0	$110,283
January 27, 2011	New Canaan Station, CT	MNCW	7	0	0	$51,500
June 27, 2010	Port Washington Station, NY	LIRR	0	0	0	$10,500
April 12, 2010	Grand Central Terminal, NY	MNCW	1	0	0	$31,500
October 21, 2009	33rd Street Terminal, NY	PATH	6	2	0	$328,000
June 12, 2009	Washington Union Station, DC	ATK	3	0	0	$19,500
March 2, 2009	New Canaan Station, CT	MNCW	1	0	0	$20,000

Date	Location	Railroad[2]	Speed (mph)	Injuries	Fatality	Damage Cost
June 20, 2008	Far Rockaway, NY	LIRR	3	0	0	$20,500
July 8, 2007	Penn Station, NY	NJT	10	1	0	$90,600
November 4, 2005	Port Washington Station, NY	LIRR	5	0	0	$15,800
October 31, 2005	Hempstead Station, NY	LIRR	3	0	0	$11,600
August 13, 2004	Grand Central Terminal, NY	MNCW	11	3	0	$50,000
December 7, 2003	New Canaan Station, CT	MNCW	5	0	0	$28,674
February 18, 2003	Port Washington Station, NY	LIRR	5	0	0	$7,900
December 14, 2002	Hoboken Terminal, NJ	NJT	0	0	0	$80,000
May 19, 2001	San Francisco Station, CA	PCMZ	2	0	0	$8,500
April 9, 2001	Flatbush Terminal, NY	LIRR	2	0	0	$8,210

[1] Data sources: FRA REA database and NTSB railroad accident reports.
[2] Railroads: Long Island Rail Road (LIRR); New Jersey Transit (NJT); Metro-North Commuter Railroad (MNCW); Northeast Illinois Regional Commuter Railroad (NIRC); Caltrain Commuter Railroad (PCMZ); Port Authority Trans-Hudson (PATH).

6.3.2 Methodology with Cost Factors

To estimate the gross safety benefit, the estimation structure is plotted in Figure 23. The categories include casualties, equipment damage, track and ROW damage, evacuations, wreck clearing, and train delays (Figure 23).

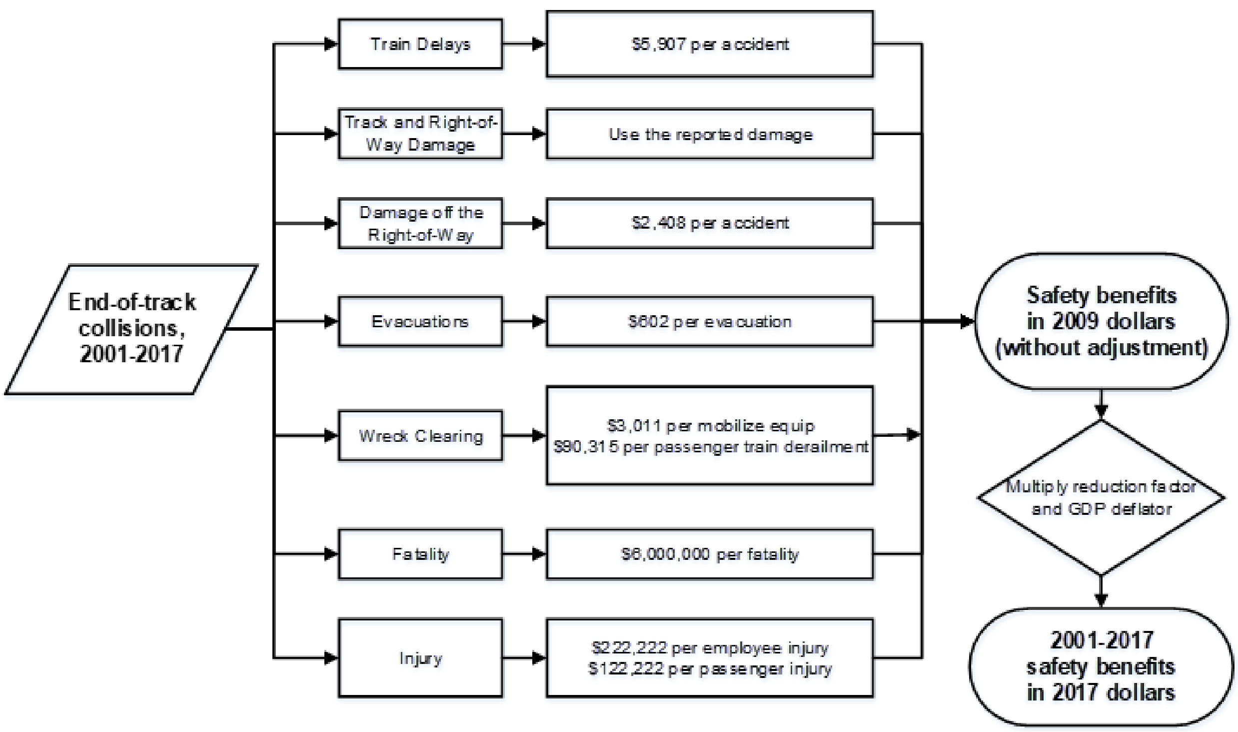


Figure 22. Methodology for Estimating PTC Safety Benefit in End-of-Track Collisions (FRA, 2009)

The cost factors are the basis for the safety benefit estimations (FRA, 2009). For example, FRA (2009) estimated the cost of passenger train delays based on "285 passengers per train (a national average), an average duration of blockage of 2 hours (which implies passenger trains per day/12 are affected), an average per train delay of 15 minutes, and an average value of passenger time of $25 per hour." Then the average cost of passenger train delay was estimated at $148

$(=285 \times \$25 \times (\frac{1}{4}) \times (\frac{24}{2}))$ in 1998 dollars, or the equivalent of $179 in 2009 dollars, to be multiplied by the number of passenger trains per day. It was assumed that 33 trains per day would run and that the cost factor for train delays would be $5,907 per accident. The amount in each cost factor is in 2009 dollars (FRA, 2009). The estimated safety benefits for PPAs below restricted speeds in 2009 constant dollars would be adjusted into 2017 constant dollars.

To clarify, in addition to statistics from FRA (2009), the latest value of a statistical life (VSL) was provided in USDOT report (FRA, 2016b), in which VSL was set as $9.6 million. However, in this section, researchers used FRA (2009) to simplify the calculation of the total safety benefits involving train delay costs, ROW damage costs, evacuation costs, and so on. The calculation method developed here can be adapted to any updated values if unit costs of all fields are provided.

Using the above methodology and end-of-track collision data from 2001–2017, the safety benefit (without adjustment) of end-of-track collisions can be estimated in 2009 constant dollars. Before the adjustment, the total safety benefit of preventing all restricted-speed-PPAs is approximately $62 million during this 17-year period (in 2009 dollars).

Furthermore, in the 2009 FRA PTC economic analysis, a reduction factor was considered and assumed that 25 percent of the estimated PPA safety benefits would be reduced through countermeasures that were already instituted. As a reliable enforcement measure, it assumes that there is no reduction in PTC effectiveness in terms of preventing end-of-track collisions. Therefore, with the 75 percent of PPA benefit reduction by other countermeasures, the estimated safety benefit would be discounted by 75 percent. In addition, current cost information uses the 2009 dollars as the unit. To use the 2017 dollar as the unit of safety benefit, inflation is taken into consideration and the damage cost in each year is also adjusted to 2017 dollars using the GDP inflator (World Bank, 2018), which was 98.793 in 2009 and 112.2 in 2017. The considerations of these two factors can be presented with Equation 6-3:

$$B_j = b_i * \alpha * \frac{\beta_j}{\beta_i} \tag{6-3}$$

Where:

B_j = safety benefits in year j. Year j = 2017

b_i = safety benefits without adjustment in year i. Year i = 2009

α = reduction factor due to the mitigated risks by other countermeasures

β_j,β_j = GDP inflator number in year i and year j

Furthermore, the potential temporal trend was analyzed with the Wald-Wolfowitz runs test, a non-parametric statistical test that checks a randomness hypothesis for a two-value data sequence and has been employed in previous studies (Liu, 2016; Zhang et al., 2019). A Wald-Wolfowitz runs test shows that there is no significant temporal trend for safety benefits per year (P-value = 0.605). As a result, the expected annual savings due to end-of-track collisions are the average safety benefits per year based on the historical accident records from 2001–2017. In summary, the total safety benefit of preventing end-of-track collisions at stub-end terminals is approximately $52.8 million (in 2017 dollars) during this 17-year period. The expected annual savings due to end-of-track collisions prevention with PPA is $3.1 million (in 2017 dollars).

6.3.3 20-Year Projected Safety Benefit

In the 2009 PTC economic analysis, FRA considered some reduction factors and a phase-in schedule of safety benefits. The 20-year projected railroad safety benefits were estimated using a 7 percent and 3 percent discount rate, which adjusts for the time value of money and allows for safety benefits, as well as following costs, to be valued in equivalent units. These equivalent units are called present values and are independent when they occur (FRA, 2009; 2016b). This section updates the total safety benefits using the collected end-of-track collisions from 2001–2017. The reduction factors and discount rates are from those used in FRA (2009).

Also, safety benefits will be phased-in as PTC systems are installed and applied. An estimated phase-in schedule of benefits comes from FRA (2009), based on the original deadline in 2015. This research assumed that the installations of PTC systems at terminals take 2 years with the identical phase-in of 50 percent. Table 9 shows the calculation of the 20-year projected safety benefits, based on the above-mentioned safety benefit reduction factors and the phase-in schedule.

Table 9. 20-Year Phase-In Analysis of PTC Benefits in End-of-Track Collisions (in 2017 Dollars)

Discount Rates		7%			3%		
Year	Phase In Percent	Discount Factor	Annual Benefit	Discounted Annual Benefit	Discount Factor	Annual Benefit	Discounted Annual Benefit
2019	50%	1.00	$1,553,562	$1,553,562	1.00	$1,553,562	$1,553,562
2020	100%	0.93	$3,107,124	$2,889,626	0.97	$3,107,124	$3,013,911
2021	100%	0.87	$3,107,124	$2,703,198	0.94	$3,107,124	$2,920,697
2022	100%	0.82	$3,107,124	$2,547,842	0.92	$3,107,124	$2,858,554
2023	100%	0.76	$3,107,124	$2,361,415	0.89	$3,107,124	$2,765,341
2024	100%	0.71	$3,107,124	$2,206,058	0.86	$3,107,124	$2,672,127
2025	100%	0.67	$3,107,124	$2,081,773	0.84	$3,107,124	$2,609,984
2026	100%	0.62	$3,107,124	$1,926,417	0.81	$3,107,124	$2,516,771
2027	100%	0.58	$3,107,124	$1,802,132	0.79	$3,107,124	$2,454,628
2028	100%	0.54	$3,107,124	$1,677,847	0.77	$3,107,124	$2,392,486
2029	100%	0.51	$3,107,124	$1,584,633	0.74	$3,107,124	$2,299,272
2030	100%	0.48	$3,107,124	$1,491,420	0.72	$3,107,124	$2,237,130
2031	100%	0.44	$3,107,124	$1,367,135	0.70	$3,107,124	$2,174,987
2032	100%	0.41	$3,107,124	$1,273,921	0.68	$3,107,124	$2,112,845
2033	100%	0.39	$3,107,124	$1,211,778	0.66	$3,107,124	$2,050,702
2034	100%	0.36	$3,107,124	$1,118,565	0.64	$3,107,124	$1,988,560
2035	100%	0.34	$3,107,124	$1,056,422	0.62	$3,107,124	$1,926,417
2036	100%	0.32	$3,107,124	$994,280	0.61	$3,107,124	$1,895,346
2037	100%	0.30	$3,107,124	$932,137	0.59	$3,107,124	$1,833,203
2038	100%	0.28	$3,107,124	$869,995	0.57	$3,107,124	$1,771,061
Total		11.33		$33,650,157	15.32		$46,047,583

In summary, the 20-year safety benefit of preventing end-of-track collisions at stub-end terminals is $33.7 million (in 2017 dollars, using a 7 percent discount rate) and $46.0 million (in 2017 dollars, using a 3 percent discount rate). The annual safety benefits are $1.7 million (in

2017 dollars, using 7 percent discount rate) and $2.3 million (in 2017 dollars, using 3 percent discount rate).

6.4 Cost Calculations of PTC Implementation at Stub-End Terminals

6.4.1 PTC Installation Cost at Stub-End Terminals

The above calculation of safety benefits covers stub-end terminals throughout the U.S. The incremental cost of proposed PTC enforcement at terminal stations should also be estimated on a national scale. First, unit costs (e.g., labor costs, material costs) are based on discussions with railroad experts and vendors over the course of risk experience in estimating PTC component costs. Secondly, the collected unit costs encompass both lower-end and higher-end expenses to account for cost variations.

- **Track mapping cost (for I-ETMS only)**. The track mapping cost in Table 10 covers the collection of data points, preparation of GIS database, and preparation of subdivision files. The collected unit cost information also acknowledges the floating elements of track mapping. More specifically, at terminal stations, the number of possible routes and the complexity of terminating tracks lead to fluctuating track mapping costs; on an open road, the number of switches and highway-rail grade crossings would have an effect on the exact track mapping cost per track mile. In summary, and the low end and high end for terminating track mapping are $7,500 and $20,000, respectively.

Table 10. Incremental Cost Information for Track Mapping

Track Mapping	Cost per Track Mile	
	Low	High
Terminals	$7,500	$20,000

- **WIU (for I-ETMS only) and transponder (for ACSES only)**. The cost information of three categories of WIUs, standalone WIU, integrated WIU at intermediate location (Int. Loc.), and integrated WIU at control point (CP), are summarized in Table 11. Each type of WIU involves three major parts, namely cost, miscellaneous material, and the labor cost to install. In particular, the labor to install a WIU is floating and driven by the amount of design, wiring, and testing required. For example, the larger the terminal, the more switches there are and hence the more wiring and testing needed. For those locations where the signal system is run by a vital microprocessor controller, there is less wiring to be done. In conclusion, the total cost of a standalone WIU are from $25,500 to $31,500, integrated WIU (intermediate location) from $12,000 to $15,000, and integrated WIU (control point) from $17,000 to $21,000. In some cases when requesting additional WIUs, a radio tower may be also needed, which costs $20,000 in material part and $4,000 in labor. Similarly, the overall cost of a transponder – the material cost of the transponder, miscellaneous materials, and labor to install – ranges from $3,300 to $3,600 due to varying locations and the complexity of transponder installation (Table 11).
- **Design cost**. In I-ETMS-type terminals, design cost mainly involves the preparation of a subdivision file with necessary measurements. In an ACSES-type terminal, some design work is needed to plug the collect information and program into the transponder. The design cost per railroad experts' judgment is estimated at $50,000 in terminals with less

than five terminating tracks and $100,000 in the terminals with over five terminating tracks.

Table 11. Incremental Cost Information for WIU and Transponder

Type of Hardware	Unit Cost	Miscellaneous Materials	Labor to Install		Total	
			Low	High	Low	High
Stand Alone WIU	$12,000	$1,500	$12,000	$18,000	$25,500	$31,500
Integrated WIU (Int. Loc.)	$6,000	$1,000	$5,000	$8,000	$12,000	$15,000
Integrated WIU (CP)	$8,000	$1,000	$8,000	$12,000	$17,000	$21,000
Transponder	$2,500	$500	$300	$600	$3,300	$3,600

- **Test cost**. In addition to equipment, material, and labor to install the hardware, train testing is necessary in most cases once the implementation is done. In the testing train, crew and train are needed to run the practical test, and the cost is around $6,000 per shift.
- **Maintenance cost**. Based on both a prior FRA report (FRA, 2009) and railroad experts' experience, the annual maintenance costs are assumed to be 10-15 percent of installed system costs at the end of the previous year.

The team used 45 as the number of stub-end terminals where PTC systems are proposed to enforce their functions; an approximate cost amount can serve as a reference point. As Figure 24 shows, an ACSES-type PTC system and an I-ETMS-type PTC system are considered, with their approximate parameters. In this case study, the gross installation cost for 39 ACSES systems and 6 I-ETMS systems is estimated at $6.9 million to $7.4 million. To be clear, these installation cost amounts do not involve maintenance costs, which is correlated with the number of years.

Cost Calculator for PTC Enforcement at Stub-End Terminals — Updated by November 2018

Required | Null | Outcome

Required Inputs

Scenarios	Quantity	Number of Tracks	Total Length of Tracks (mile)	Train Testing (shift)	Number of WIU needed	Type of WIU	Additional Radio Tower is Needed?
Stub End Terminal with ACSES System	24	4	2.5	2			
	15	8	5	2			
Stub End Terminal with I-ETMS System	3	4	2.5	2	1	Stand Alone WIU	NO
	3	8	5	2	1	Stand Alone WIU	NO

Outcomes

Scenarios	Cost ($)	
	Low End	High End
Stub End Terminal with ACSES System	6,019,200	6,278,400
Stub End Terminal with I-ETMS System	843,750	1,161,000
Total	6,862,950	7,439,400

Figure 23. Installation Cost Calculator for Multiple Stub-End Terminals

An Excel-based calculator was developed to estimate the gross incremental installation cost (without maintenance cost) for both system types. Additionally, any railroad or corridor can utilize this calculator for cost estimations provided the essential parameters exist, such as the number of stub-end terminals, the quantity of terminating tracks in each terminal, and the length of these tracks.

6.5 20-Year Projected PTC Implementation Cost with Maintenance Cost

This section calculates a life cycle cost over a service life of 20 years and is based on a 2009 FRA study of PTC economics. Annual maintenance costs are assumed to be 10 percent~15 percent of installed system costs at the end of the previous year. Ten percent is used in the low-end cost estimation and 15 percent is used in the high-end cost estimation. Similar to previous safety benefit calculations, the NPV is considered in the cost calculation and thus the discounted life cycle costs are calculated using both 3 percent and 7 percent annual discount factors – consistent with the 2009 FRA study. Table 12a and Table 12b present low-end service costs and high-end service costs, respectively. In addition, a phase-in schedule also assumed that the installations of PTC systems at terminals take 2 years with the identical 50 percent phase-in. Based on the installation cost, maintenance cost, and the phase-in schedule, 20-year projected costs are calculated in Table 12. In summary, the 20-year low-end costs of PTC implementations at stub-end terminals are $12.6 million (2017 dollars, using a 7 percent discount rate) and $15.2 million (2017 dollars, using a 3 percent discount rate). The 20-year high-end costs of PTC implementations at stub-end terminals are $21.1 million (2017 dollars, using a 7 percent discount rate) and $26.1 million (2017 dollars, using a 3 percent discount rate). The maintenance costs exceed the initial procurement costs over the 20-year period, as shown in Table 12.

Table 12. 20-Year Service Life Cost of PTC Implementation Cost at Stub-End Terminals

(a) Lower-End

Year	Phase In Percent	Installed Costs	Maintenance Costs	7%			3%		
				Discount Factor	Annual Cost	Discounted Annual Cost	Discount Factor	Annual Cost	Discounted Annual Cost
2019	50%	$3,086,100	$308,610	1.00	$3,394,710.00	$3,394,710	1.00	$3,394,710.00	$3,394,710
2020	100%	$3,086,100	$617,220	0.93	$3,703,320.00	$3,444,088	0.97	$3,703,320.00	$3,592,220
2021	100%	$0	$617,220	0.87	$617,220.00	$536,981	0.94	$617,220.00	$580,187
2022	100%	$0	$617,220	0.82	$617,220.00	$506,120	0.92	$617,220.00	$567,842
2023	100%	$0	$617,220	0.76	$617,220.00	$469,087	0.89	$617,220.00	$549,326
2024	100%	$0	$617,220	0.71	$617,220.00	$438,226	0.86	$617,220.00	$530,809
2025	100%	$0	$617,220	0.67	$617,220.00	$413,537	0.84	$617,220.00	$518,465
2026	100%	$0	$617,220	0.62	$617,220.00	$382,676	0.81	$617,220.00	$499,948
2027	100%	$0	$617,220	0.58	$617,220.00	$357,988	0.79	$617,220.00	$487,604
2028	100%	$0	$617,220	0.54	$617,220.00	$333,299	0.77	$617,220.00	$475,259
2029	100%	$0	$617,220	0.51	$617,220.00	$314,782	0.74	$617,220.00	$456,743
2030	100%	$0	$617,220	0.48	$617,220.00	$296,266	0.72	$617,220.00	$444,398
2031	100%	$0	$617,220	0.44	$617,220.00	$271,577	0.70	$617,220.00	$432,054
2032	100%	$0	$617,220	0.41	$617,220.00	$253,060	0.68	$617,220.00	$419,710
2033	100%	$0	$617,220	0.39	$617,220.00	$240,716	0.66	$617,220.00	$407,365
2034	100%	$0	$617,220	0.36	$617,220.00	$222,199	0.64	$617,220.00	$395,021
2035	100%	$0	$617,220	0.34	$617,220.00	$209,855	0.62	$617,220.00	$382,676
2036	100%	$0	$617,220	0.32	$617,220.00	$197,510	0.61	$617,220.00	$376,504
2037	100%	$0	$617,220	0.30	$617,220.00	$185,166	0.59	$617,220.00	$364,160
2038	100%	$0	$617,220	0.28	$617,220.00	$172,822	0.57	$617,220.00	$351,815
Total				11.33		**$12,640,666**	15.32		**$15,226,817**

(b) Higher-End

Year	Phase In Percent	Installed Costs	Maintenance Costs	7%			3%		
				Discount Factor	Annual Cost	Discounted Annual Cost	Discount Factor	Annual Cost	Discounted Annual Cost
2019	50%	$4,068,450	$610,268	1.00	$4,678,717.50	$4,678,718	1.00	$4,678,718	$4,678,718
2020	100%	$4,068,450	$1,220,535	0.93	$5,288,985.00	$4,918,756	0.97	$5,288,985	$5,130,315
2021	100%	$0	$1,220,535	0.87	$1,220,535.00	$1,061,865	0.94	$1,220,535	$1,147,303
2022	100%	$0	$1,220,535	0.82	$1,220,535.00	$1,000,839	0.92	$1,220,535	$1,122,892
2023	100%	$0	$1,220,535	0.76	$1,220,535.00	$927,607	0.89	$1,220,535	$1,086,276
2024	100%	$0	$1,220,535	0.71	$1,220,535.00	$866,580	0.86	$1,220,535	$1,049,660
2025	100%	$0	$1,220,535	0.67	$1,220,535.00	$817,758	0.84	$1,220,535	$1,025,249
2026	100%	$0	$1,220,535	0.62	$1,220,535.00	$756,732	0.81	$1,220,535	$988,633
2027	100%	$0	$1,220,535	0.58	$1,220,535.00	$707,910	0.79	$1,220,535	$964,223
2028	100%	$0	$1,220,535	0.54	$1,220,535.00	$659,089	0.77	$1,220,535	$939,812
2029	100%	$0	$1,220,535	0.51	$1,220,535.00	$622,473	0.74	$1,220,535	$903,196
2030	100%	$0	$1,220,535	0.48	$1,220,535.00	$585,857	0.72	$1,220,535	$878,785
2031	100%	$0	$1,220,535	0.44	$1,220,535.00	$537,035	0.70	$1,220,535	$854,375
2032	100%	$0	$1,220,535	0.41	$1,220,535.00	$500,419	0.68	$1,220,535	$829,964
2033	100%	$0	$1,220,535	0.39	$1,220,535.00	$476,009	0.66	$1,220,535	$805,553
2034	100%	$0	$1,220,535	0.36	$1,220,535.00	$439,393	0.64	$1,220,535	$781,142
2035	100%	$0	$1,220,535	0.34	$1,220,535.00	$414,982	0.62	$1,220,535	$756,732
2036	100%	$0	$1,220,535	0.32	$1,220,535.00	$390,571	0.61	$1,220,535	$744,526
2037	100%	$0	$1,220,535	0.30	$1,220,535.00	$366,161	0.59	$1,220,535	$720,116
2038	100%	$0	$1,220,535	0.28	$1,220,535.00	$341,750	0.57	$1,220,535	$695,705
Total				11.33		**$21,070,503**	15.32		**$26,103,175**

6.6 BCA

The above calculation of safety benefits and incremental costs covers stub-end terminals in the U.S. To evaluate the benefit-cost analysis, two metrics were used: NPV and BCR. NPV is equal to the benefits minus costs over a specified service life (e.g., 20 years), and the BCR is equal to the benefits divided by the costs. These two major outputs were employed in previous studies. For example, FRA developed GradeDec, a highway-rail crossing investment analysis tool to provide grade crossing investment decision support (FRA, 2018b).

In finance, the NPV is the summation of the present value of a series of present and future cash flows. In this report, the NPV of PTC implementation at stub-end terminals is calculated as the sum of the safety benefits of reduced end-of-track collisions, minus the total cost associated with PTC installation and maintenance over the service years (e.g., 20 years), during which the safety benefits and costs are expected to accrue. This measure has been used in a previous study of the benefit-cost analysis of infrastructure improvement for derailment prevention (Liu et al., 2010) and a benefit-cost analysis of a heavy-haul railway track upgrade (Liu et al., 2011). As shown in the equation below, the monetary values of benefits and costs were discounted to constant 2017 dollars:

$$NPV = \sum_{i=1}^{Y} \frac{B_i}{(1+d)^i} - \sum_{i=1}^{Y} \frac{C_i}{(1+d)^i} \tag{6-4}$$

Where:

Y= time span over which the NPV is calculated; in this study, Y=20

B_i = safety benefits of reduced end-of-track collisions in year *i*

C_i = Costs of PTC implementation at stub-end terminals in year *i*

d = annual discount rate; this study used 3 percent and 7 percent

BCR is also an indicator used in the BCA. It was used in the calculation of nationwide PTC economic analysis (FRA, 2009) and can be calculated via below equation:

$$BCR = \frac{\sum_{i=1}^{Y} B_i}{\sum_{i=1}^{Y} C_i} \tag{6-5}$$

Where:

B_i = safety benefits of reduced end-of-track collisions in year *i*

C_i = Costs of PTC implementation at stub-end terminals in year *i*

Y= time span over which the NPV is calculated; in this study, Y=20

With two indicators that were commonly used in BCA, the analytical results are summarized in Table 13.

Table 13. BCA of PTC Implementation in Stub-End Terminals

		7% Discount Rate		3% Discount Rate	
		20-year total values	Annualized values	20-year total values	Annualized values
Safety Benefits		$33,650,157	$1,682,508	$46,047,583	$2,302,379
Incremental Costs	Low End	$12,640,666	$632,033	$15,226,817	$761,341
	High End	$21,070,503	$1,053,525	$26,103,175	$1,305,159
NPV	Low End	$12,579,654	$628,983	$19,944,408	$997,220
	High End	$21,009,491	$1,050,475	$30,820,765	$1,541,038
Benefit-Cost Ratio	Low End	1.7	1.7	1.8	1.8
	High End	2.8	2.8	3.1	3.1

Note: *Costs* indicate the summation of installation cost and maintenance costs; it is presented with lower-end values and higher-end values.

The average annual NPV would be around $800,000 (2017 dollars, using a 7 percent discount rate) and $1.3 million (2017 dollars, using a 3 percent discount rate). In other words, the benefit-cost analysis shows a significant surplus, sufficient to cover installation and maintenance costs for a 20-year service life. Moreover, BCR is around 2 or even more, which indicates that the 20-year safety benefits would be approximately 2 times the 20-year costs.

PTC implementation at stub-end terminals yields a significant economic advantage (benefits higher than costs), provided it is kept for a reasonable lifetime (e.g., 20 years or longer). It was also noticed that the total costs are "recovered" in terms of benefits in around 5 years. In other words, starting from the 5th year of PTC implementation at stub-end terminals, the total safety benefits would be greater than total costs (summation of installation and corresponding maintenance costs). Per the cost calculator, either the number of stub-end terminals or the parameters in each scenario can be updated based on more practical data or railroad-specific data information in the future. The cost-to-benefit analysis only provided an example for the nationwide PTC enforcement at stub-end terminals.

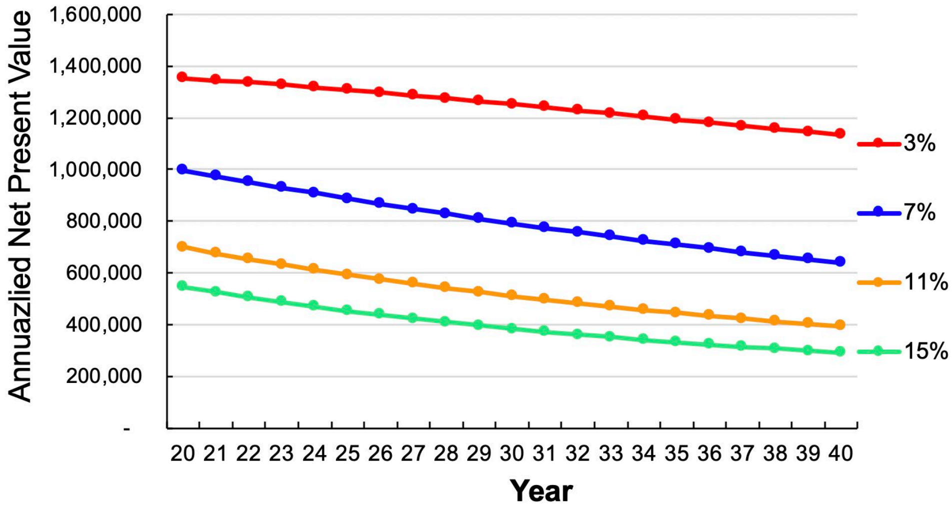
6.7 Sensitivity Analysis

In this section, a sensitivity analysis investigates the impacts of assumed parameters – discount rate, service life, and maintenance costs on the NPV calculation and BCR – based on prior studies and FRA guidance (FRA, 2016b). They may include some level of uncertainty attributable to the use of preliminary benefit-cost estimates. FRA guidance (FRA, 2016b) suggested that the benefit-cost analysis should include a sensitivity analysis if key data elements are uncertain. This study used the nationwide PTC implementation as an example and took the previous results as a base case. A sensitivity analysis was applied to illustrate how its results would change if this analysis employed alternative values for those elements (e.g., discount rate, service life, maintenance costs). In addition, to present the sensitivity analysis explicitly, the section simplified the cost outputs via a medium value, instead of presenting both low end and high end.

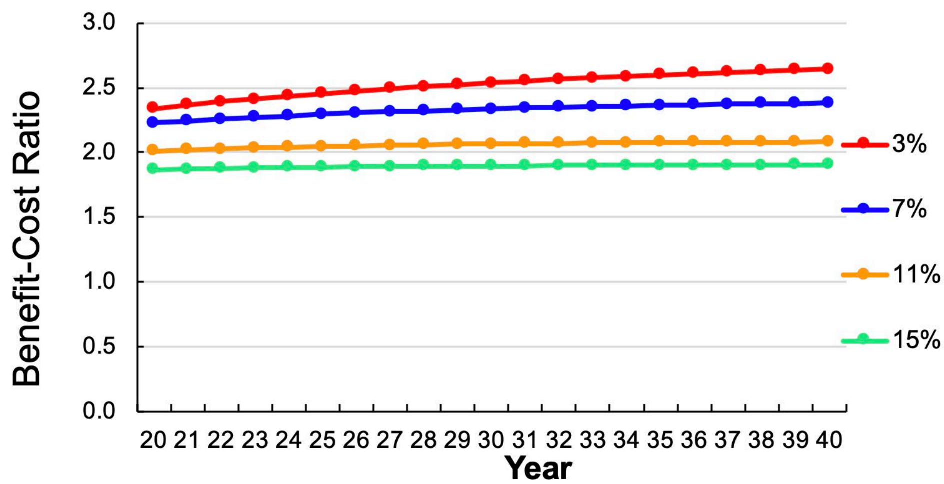
6.8 Discount Rate

Per the formula in the equation above, NPV and BCR are critically affected by the discount rate. The above base cases use 3 percent and 7 percent as two discount rates, which are referred to in two FRA reports (FRA, 2009; 2016b). It is evident that the use of different discount rates has a substantial impact on the results (Figure 25). Lower discount rates would have larger annualized NPVs and larger BCRs, relatively. A 3 percent discount rate resulted in a positive, larger NPV and somewhat larger BCR at any service life within the 20–40 years considered. On the other hand, a 15 percent discount rate still has positive NPV but the values of both NPV and BCR are relatively smaller.

Also, with an extended study period (i.e., service life), annualized NPV decreases steadily while BCR increases slightly. This is consistent for all discount rates considered in this sensitivity analysis. It This indicates that the economic advantages of implementing PTC at stub-end terminals decrease (though they remain positive) from a longer-service-life perspective. However, the ratio of safety benefits to costs remains stable or even shows a slight increase.



(a) Annualized NPV



(b) BCR

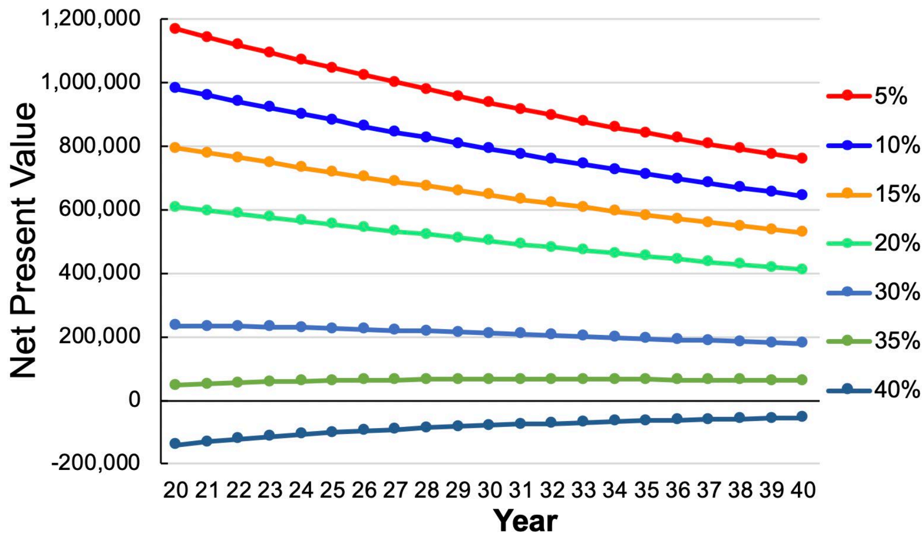
Note: To simplify the sensitivity analysis, the cost part takes the mean value of high-end cost and low-end cost.

Figure 24. Sensitivity Analysis of (a) Annualized NPV and (b) BCR Affected by Discount Rate

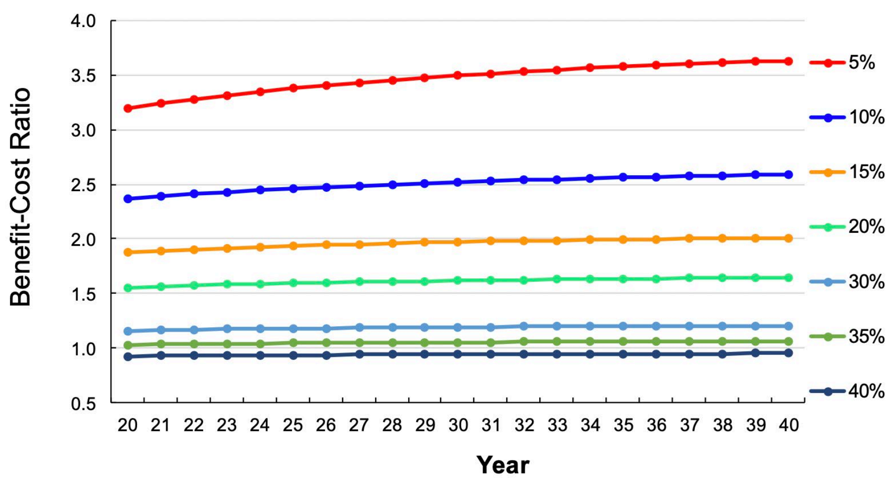
6.9 Maintenance Cost Ratio

This subsection considers 6 different ratios of maintenance costs to installation costs: 5 percent, 15 percent, 20 percent, 30 percent, 35 percent, and 40 percent. It is evident that the use of different maintenance cost ratios has a substantial impact on the results (Figure 26).

A lower maintenance cost ratio would have a larger annualized NPV and larger BCR. A 5 percent maintenance cost rate resulted in a positive, larger NPV and somewhat larger BCR at any service life within 20–40 years. Use of a 20 percent discount rate still showed positive NPV, but the values of both the NPV and BCR were relatively smaller. On the other hand, the use of a 40 percent discount rate showed a negative NPV, indicating that the total benefits in a service life would be lower than total costs once the annual maintenance cost is equal to or greater than 40 percent of installed PTC costs. With a more extended study period (service life), annualized NPV decreases steadily while the BCR increases slightly. This indicates that the economic advantages/disadvantages of PTC implementation at stub-end terminals decrease with a longer service life perspective, but the relative metric in terms of the comparison between safety benefits and costs is stable or even increases a little. When the maintenance cost ratio is larger than 36 percent, the NPV would be a negative value. This indicates that when the annual maintenance cost is larger than 36 percent of installed PTC costs, the total benefits in a service life would be lower than total costs.



(a) Annualized NPV



(b) BCR

Note: To simplify the sensitivity analysis, the cost part takes the mean value of high-end cost and low-end cost.

Figure 25. Sensitivity Analysis of a) Annualized NPV and b) BCR Affected by Maintenance Cost Ratio

7. Operational Impact Assessment

This section studies the operational impacts of operating practices based on the proposed restricted speed PTC enforcement. According to the design and procurement of all improvements or modifications to PTC from the ConOps, an operational impact assessment for ACSES and/or I-ETMS positive train control systems was conducted for this report. Several scenarios will be studied to fully describe the operational impact on capacity and run-time for each case.

First, in the macro-level assessment, each scenario was analyzed based on the proposed ConOps and deep expertise in PTC technology. Second, the micro-level analysis employed a statistical simulation tool (e.g., Monte Carlo simulation) to quantitatively evaluate the impact of PTC on operations at stub-end terminals, which may have a certain level of capacity impacts. A generic model of a known rail line was used to conduct this micro-level simulation under controlled conditions for the purpose of determining any operational impacts on terminal capacity and operations. These two steps contributed to a comprehensive assessment of operational impact in PTC enforcement at restricted speeds.

Per previous discussions, the operational impact at stub-end terminals with I-ETMS systems would not be negligible. To prove this assertion quantitatively, a Monte Carlo simulation was employed to analyze the capacity difference between stub-end terminals with and without PTC systems. Differing from mainline operation, which is primarily concerned with moving trains between two end points, train operations at terminals consider the movement of trains among numerous facilities on multiple routes. A Monte Carlo simulation involves large numbers of running iterations with inputs to the simulation randomly assigned based on the practical distribution and limits that define the system. Because of the wide range of parameters and various uncertainties behind these variables, a Monte Carlo simulation could be the preferred method in operational impacts, instead of deterministic evaluations.

As shown in Figure 22, with the I-ETMS system, station tracks could be mapped (Figure 22) to obtain exact distances between the end of the bumping posts and a point where the train was able to obtain a good GPS signal. Restricted speed would be enforced if a train occupied a terminal track. For the system to know how far to allow the train to travel before enforcing a positive stop, it would have to know the position of every switch in the route to determine the distance to the bumping post. This would require the installation of a WIU to monitor the position of the switches. The train would query the WIU via its data radio to obtain this information. Once the route was determined, the system would know the allowable distance that it could travel before reaching the bumping post. The I-ETMS system would then calculate a braking profile based on the current speed of the train and the distance to the bumping post and enforce a positive stop short of the stop target if the system determines that at its current speed the train will not stop or slow sufficiently.

In either a stub-end terminal with or without the I-ETMS system, not only are trains required to be operating at restricted speeds, but it is also necessary to stop short of hitting the bumping post on any route. For bumping post protection with I-ETMS systems, a WIU is needed to determine the route the train will take for the onboard computer to be able to stop the train short of the bumping post. But with a failed WIU or a failed radio, the onboard system would not know the exact distance to the bumping post and would have to take the worst-case (shortest) distance. This could result in a stop enforcement well short of the bumping post. In general, the train would be delayed from reaching a point within the platform area where it would be able to discharge passengers. Besides, this delay increases the time that the train would occupy individual track segments and the end of the train would be blocking the path of other trains, thereby delaying them from either entering or leaving their tracks, which is likely to lead to congestion. To simulate the capacity analysis from I-ETMS system enforcement at stub-end terminals, three major scenarios, which are stub-end terminals without I-ETMS system, stub-end terminals with I-ETMS system and without failure, and stub-end terminals with I-ETMS system with failure, were considered and compared.

With ACSES, the ATC system can enforce the train speeds to the wayside signal indication (such as restricted speed indication). The proposed solution is to divide the terminal into two zones as shown in Figure 21b. As the train reaches the end of the full ACSES territory, the last transponder set tells the onboard ACSES system that it has entered "Out of ACSES Territory" (Zone 1). The second zone begins at the entering end of each platform. The first transponder set (T1) makes the system re-enter ACSES territory and provides PTS information, targeting the end of the platform track or bumping post as the stop target. This transponder set also provides linking distance information to the next transponder set (T2). The first transponder set needs to be located at a distance greater than or equal to the braking distance needed to stop the train. The second transponder set (T2) provides redundancy to the first set and better stopping accuracy. This transponder set provides a PTS with the distance to the bumping post and allows the train to safely stop short of the bumping post or end of track (Figure 21).

7.1 General Principles in Operational Impact Assessment

7.1.1 Train Braking Algorithm

CE-205 is a passenger train safe braking standard adopted by Amtrak (National Railroad Passenger Corporation) and commuter railroads (e.g., Caltrain, SunRail) in the U.S. (Amtrak, 2012). The CE-205 braking distance curve is based on an average performance of 1.1 mph per second deceleration rate. In the calculation of stopping distances, this rate is de-rated by 25 percent as a safety factor, resulting in a revised value of 0.88 mph per second. In addition, an 8-second delay time is considered due to cab signal delay, brake propagation delay, and engineer reaction delay. The estimation equation of CE-205 stopping distance is shown in Figure 27. For example, if a train traveling with 20 mph applies brake and stops, the stopping distance is 568.032 feet. In the braking curves developed by Mokkapati and Pascoe (2011), the stopping distance with an 8-second delay is $270.73 + 29.34 \times 8 = 505.45$ ft.

The CE-205 braking algorithm is for train operations without a PTC system, in which the train engineer is responsible for speed reduction and PTS. In terms of braking applied by the PTC systems, the brake delay time in the PTC-induced braking algorithm is expected to be shorter than manual operation. Mokkapati and Pascoe (2011) concluded that the brake delay time is related to locomotive positions and train length:

$$Td = CF * (0.0013 * (Train\ Length) + 1.8322\ s) \tag{7-1}$$

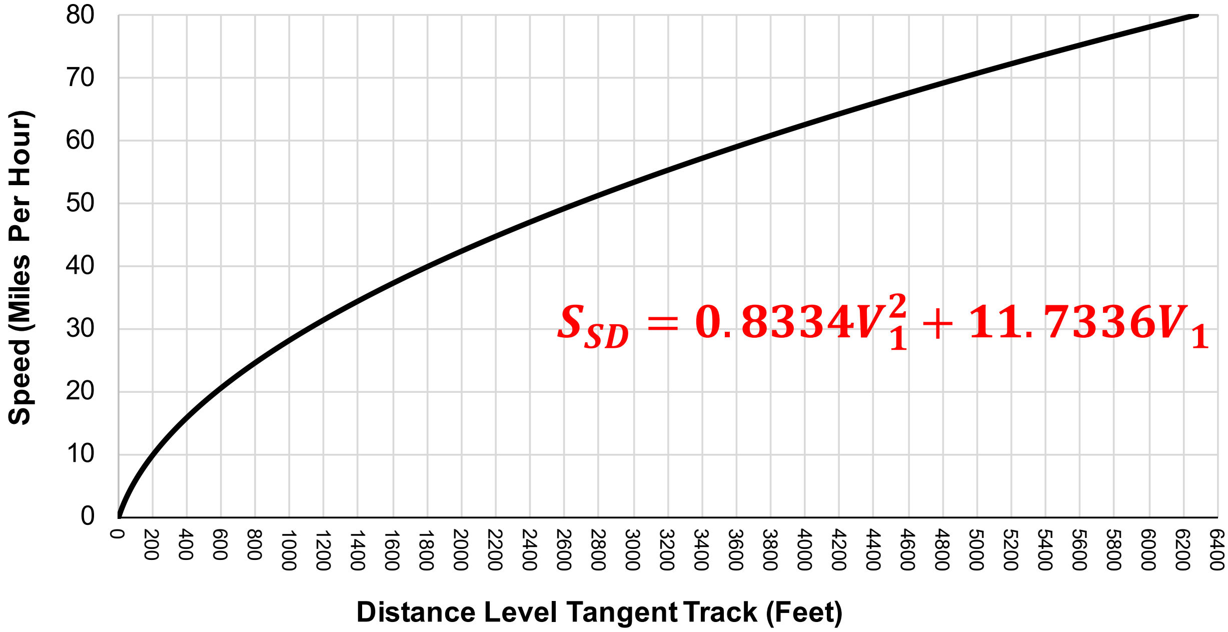
Where,

Td = the brake propagation delay time (seconds)

CF = the correction factor (e.g., 1.11 for the passenger trains with the locomotives at head end only and 1.08 for the push-pull passenger trains)

Train length = the length of the entire train in feet

Taking one passenger train consisting of 6 cars (1 locomotive at head end and 5 passenger cars) with a train length of 491 feet ($1 \times 66\text{ft} + 5 \times 85\text{ft}$) as an example, the brake delay time in PTC-induced brake algorithm would be 2.74 seconds.



Notes: This braking algorithm is for train operation on level tangent track. For ascending grades, the equivalent distance is $[(\textit{braking distance on level tangent track}) \times (6 + G)]/6$, and for descending grades, it is $[(\textit{braking distance on level tangent track}) \times (4 - G)]/4$, where G is the grade.

Figure 26. CE-205 Braking Distance Curve

7.1.2 PTC Component Failure

In terms of PTC failures, onboard system failure, communication failure, and wayside system failure are considered potential PTC component failures. In ACSES-type PTC systems, the failure of the onboard system, communications, and/or transponders would result in the system being cut out and the train stopping before the bumping post, still relying on the engineer's operation. In I-ETMS-type PTC systems, the failed onboard computer would cut out PTC enforcement. Simultaneously, all terminating tracks are mapped in the proposed ConOps for the I-ETMS system, and a WIU and communication radio provide information about the route that the train will take. Thus, restricted speed and bumping post collision prevention will still be enforced throughout the terminal, even if the WIU and/or radio have failed. However, failure of the train to determine the route due to a failed WIU or a failed radio or communication link between the train and the WIU would prevent the system from accurately stopping the train short of the bumping post. The system should be designed to stop the train after traveling the shortest mapped distance in case it cannot determine the exact route it is taking (Figure 28).

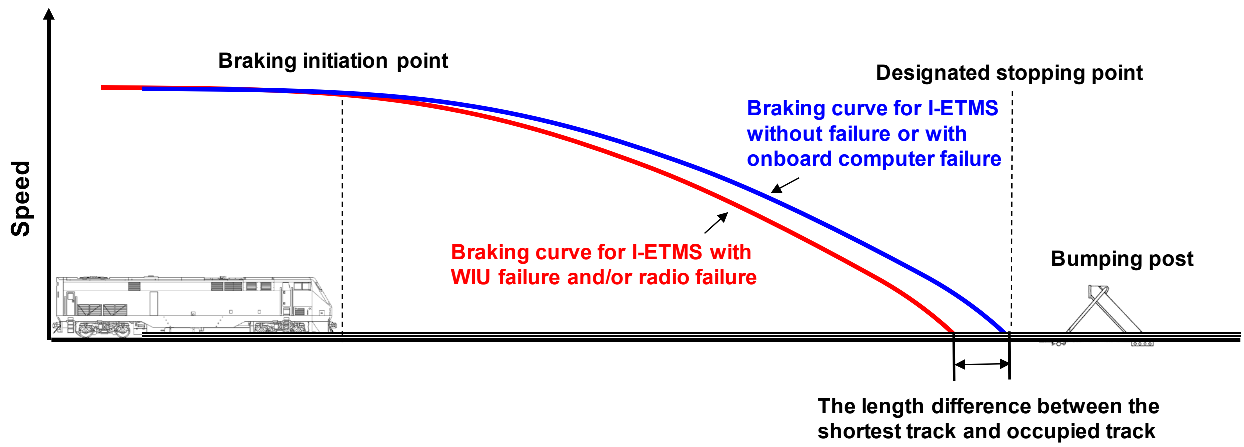


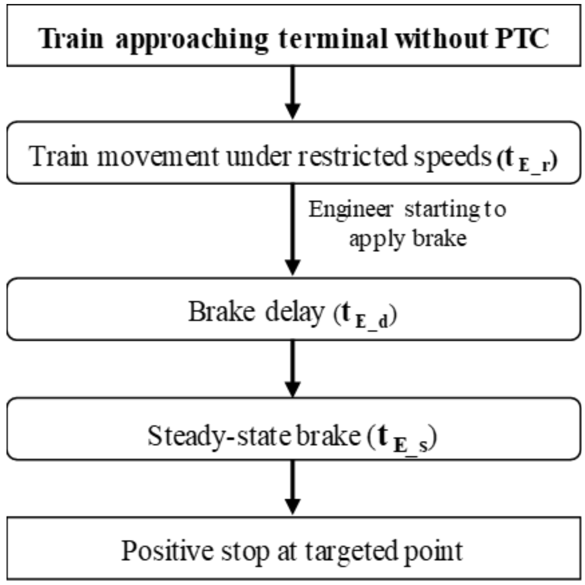
Figure 27. Illustrative Braking Curves Involving I-ETMS Component Failures

7.2 Monte Carlo Simulation Process

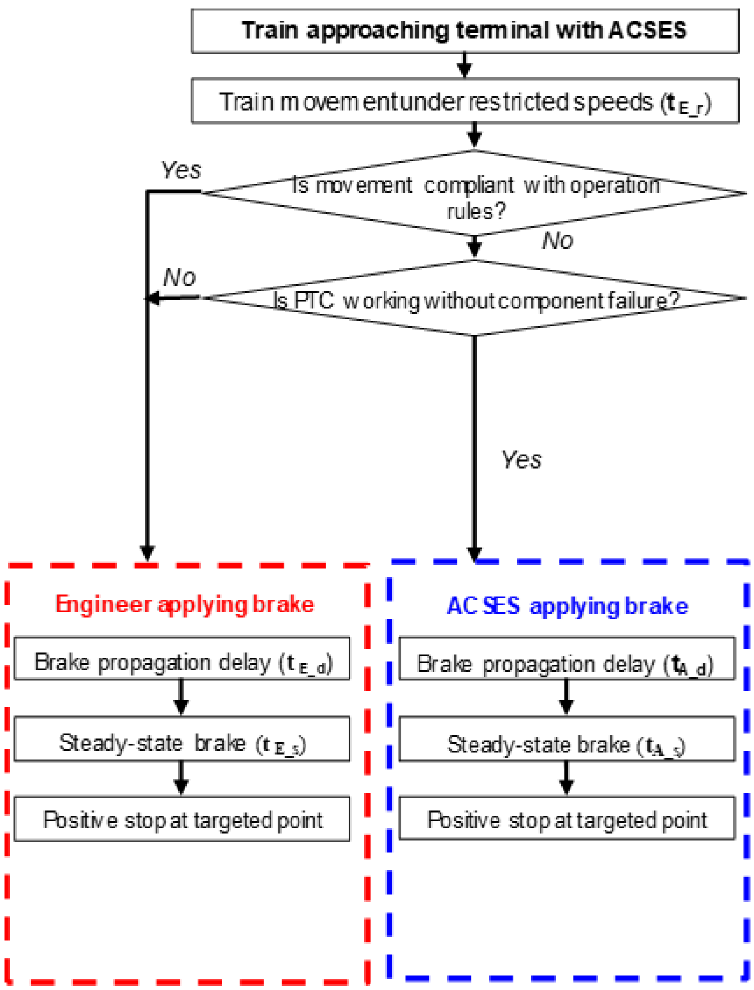
The quantitative operational impact analysis of terminal capacity can be accomplished by a Monte Carlo simulation involving the key principles. A simulation involves replicating the real-world process of a train operation over time in a stub-end passenger terminal. The simulation method can serve well as a representation of the dynamic behavior of a system by moving it from state to state in accordance with pre-defined constraints, and a considerably large iteration of simulation (e.g., 1 million or more) can consider the stochasticity that exists in the practical train operations within the service life. As an early exploration into the quantitative analysis of terminal train operational impact, this study adopts train operating duration on the terminating track as the primary assessment criterion, drawing inspiration from previous research (Woodburn, 2017). The operational time duration serves as a comprehensive indicator, capturing both the actual train arrival time and any delays incurred en route by comparing the actual with the planned time. This metric is integral to understanding network capability and resilience. To address variations and uncertainties such as engineer attentiveness, brake efficiency, environmental conditions, rail adhesion, and system processing speed, a Monte Carlo simulation is employed. This simulation assumes that brake delay time and steady-state brake rate follow normal distributions. The mean values of these factors adhere to established braking algorithms, while variances are justified based on railroad expertise. The study compares three scenarios: terminal operation without a PTC system (used as a benchmark), terminal operation with an ACSES-type PTC system, and terminal operation with an I-ETMS-type PTC system.

7.2.1 Base Case Simulations

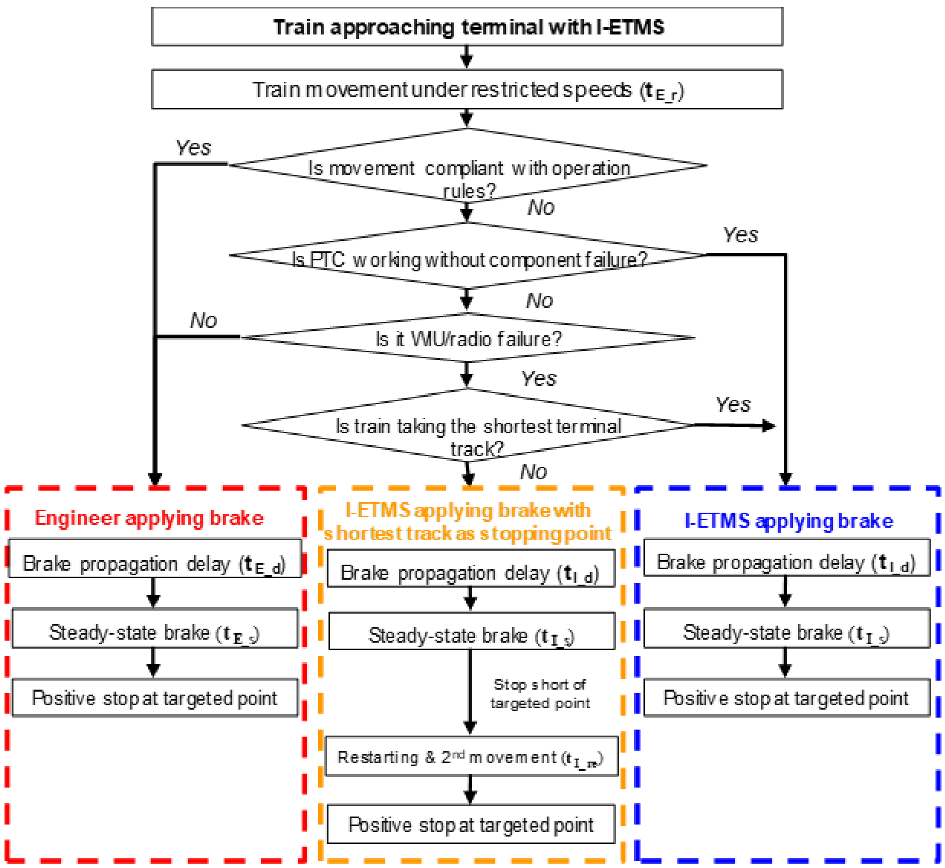
In the base case, the train approaching a terminal is operated by the train engineer and no train control system can apply penalty brake even if the train movement is noncompliant. These simulations are executed based on the train operational methods currently used in the terminating stations. In general, three major phases are involved in this base case, which are train movement under restricted speeds (without slowing down, t_{E_r}), brake delay involving reaction time (t_{E_r} t_{E_d}), and steady-state braking duration t_{E_s}) (Figure 29a). Then the total time duration for a train approaching into terminal and stopping at targeted point before bumping post equals the summation of t_{E_r}, t_{E_d}, and t_{E_s}.



(a) Terminal Train Operation without PTC (Base Case)



(b) Terminal Operation with ACSES-Type PTC



(c) Terminal Operation with I-ETMS -Type PTC

Figure 28. Flowchart of Train Movements in a Terminal Area a) without a PTC System; b) with an ACSES System; and c) with an I-ETMS System

7.2.2 I-ETMS-Type PTC System Involved Terminal Simulations

Similarly, the proposed I-ETMS system in a terminating station would be monitored with respect to its speed limits and authority. The PTC system activates braking enforcement to safely halt the train before colliding with the bumping posts only in the event of human errors leading to a violation. . In addition, this practical operational impact analysis section also takes PTC component reliability into account. Three main types of I-ETMS component failure are covered and are likely to result in different scenarios. The occurrence of onboard locomotive system failure would lead to the failure of PTC braking application. In this case, the train movement would still be controlled by the engineer. If WIU or data radio fails, the onboard system would not know the exact distance to the bumping post and would have to take the worst-case (shortest) distance. Therefore, the train approaching terminal with WIU failure or data radio failure is consist of four phases, which are train movement under restricted speed (t_{I_r}), reaction time (t_{I_d}), effective braking time with steady-state brake (t_{I_s}), restarting & second movement time (t_{I_re}).

7.2.3 ACSES-Type PTC System Involved Terminal Simulations

Conducted within the context of the stub-end terminal, these simulations incorporate the proposed Positive Train Control (PTC) enforcement. The PTC system, ensuring robust monitoring of train movement in accordance with speed limits and authority, activates braking enforcement in the event of human errors or violations. For instance, in systems like ACSES, the PTC system intervenes to safely bring the train to a stop before reaching the bumping posts. The train stopping before the end of the terminating track would rely on an engineer's operation. In addition to the first condition in Figure 29b ("is movement compliant with operation rules"), the ACSES component failure(s) (e.g., transponder failure, onboard transponder antenna failure, and onboard computer failure) also play a key role in the simulation of ACSES's operational impact. As stated before, the occurrence of any ACSES-type PTC system component failures would cut off the PTC system and train stopping at targeted point would still rely on the locomotive engineer. Figure 29b depicts the process of train stopping at the designated point for two cases: 1) a train stopping at a targeted point with the ACSES function (no component failure), or 2) the train stopping due to either compliant train movement or component failure(s) within the ACSES system.

7.2.4 Time Duration Assumptions with Uncertainties

The time length in each zone involves uncertainties and depends on various factors. For example, reaction time varies with the degree of an engineer's attentiveness. The time length of effective braking depends on the total weight of the train, brake shoe friction, track adhesion, and other factors. Therefore, each stochastic time length is assumed to follow a certain statistical distribution (Table 14).

Table 14. Assumed Statistical Distributions for Time Length

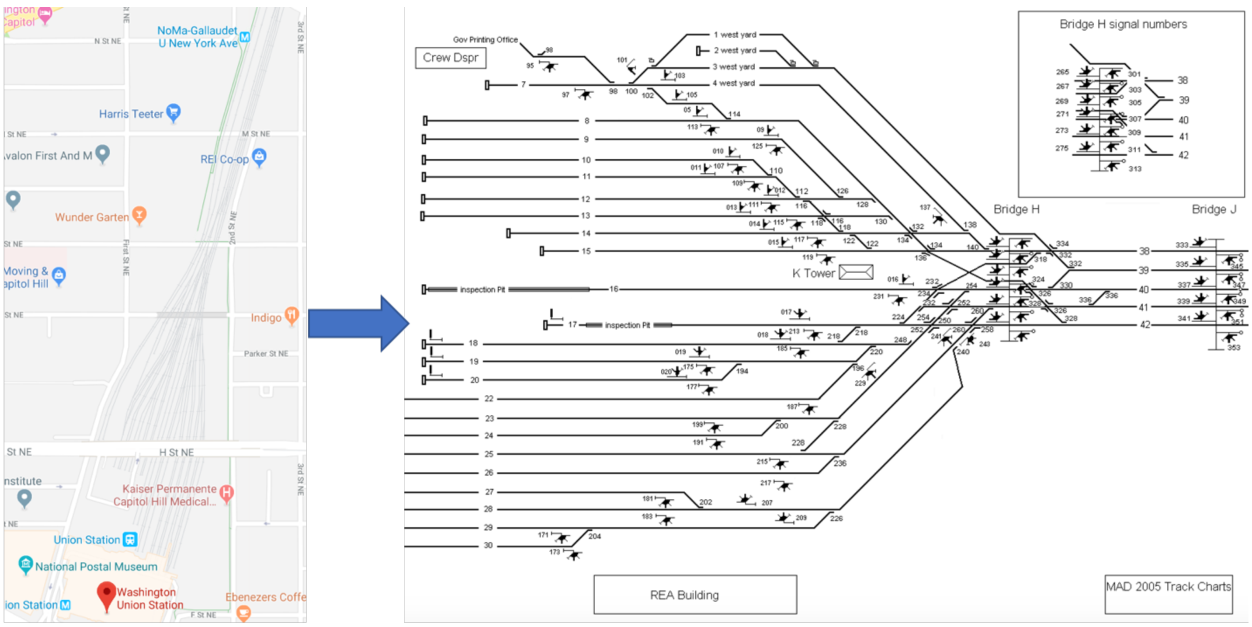
Type		Distribution	Effecting factors
Without PTC system	Brake delay time	t_{E_d} ~ *Normal distribution*	Engineer's attentiveness; etc.
	Steady-state braking time	t_{E_s} ~ *Normal distribution*	The efficiency of braking, etc.
With PTC system	Brake delay time	t_{A_d}, t_{I_d} ~ *Normal distribution*	PTC system processing speed and signal transmitting speed; etc.
	Steady-state braking time	t_{A_s}, t_{I_s} ~ *Normal distribution*	Remaining distance from PTC being in function to end of track; environment (e.g., adhesion), etc.
	Restarting & 2nd movement time, for I-ETMS only	t_{I_re} ~ *Uniform distribution*	The speed to raising air pressure in the brake pipe; time to compare stopping point against targeted point, the track length error between real track and shortest track, etc.

For example, it assumes that the brake propagation delay time follows normal distribution. A train brake applied by a PTC system will have T_d calculated as the mean value in the normal distribution, while a train engineer applying the brake will have greater mean value and variance due to longer reaction time and larger uncertainties from manual operation. To initiate a restart and execute the second movement within the terminal using an I-ETMS system, the time length varies with the track length difference between the targeted track and the shortest track that is implemented as the worst-case distance if PTC equipment fails.

7.3 Case Study in Operational Impact Assessment

7.3.1 A Typical Stub-End Terminal – Washington Union Station

To explain the operational impact assessment of a PTC enforcement at a stub-end terminal, this section develops a case study based on the track layout and train operations at Washington Union Station. This station and has 22 tracks, 13 of which are terminating tracks. It mainly provides services for Amtrak, Maryland Area Regional Commuter Rail (MARC), and Virginia Railway Express (VRE). Amtrak operates around 85 trains daily that consist of primarily Northeast Corridor services (e.g., Acela Express and regional trains), serving over 5 million passengers (boardings and alightings) in 2017 (Amtrak, 2018). The track layout of Washington Union Station is as shown in Figure 30.



From Google Map (scaled map)

From Amtrak (2006) (nonscaled map)

Figure 29. Washington Union Station Track Layout

This study uses the train schedule in Washington Union Station as an example. It assumes 300 trains approaching the terminal daily. The analysis of the terminal explicitly examines simulated operations covering a 50-year period (equivalent to 5,475,000 train operations) in the terminal. During this period, the time durations needed from passing the last signal bridge (Bridge H in Figure 30) to stopping safely before the end of tracks are simulated and captured with Monte Carlo simulation. In this example, it is assumed that the maximum authorized speed (MAS) is 15 mph (22ft/s), which is the maximum speed after entering Washington Union Station. Terminating tracks in Washington Union Station start from the K Signal Bridge. In this study, track lengths of terminating track with MTEA vary between 2,460 and 2,760 feet.

In addition to the assumption in the distribution of time lengths, the probability of a specific scenario occurrence is also listed in Table 15.

Table 15. Assumptions in the Occurrence of Specific Scenarios

(a) In I-ETMS

Parameters	Definition	Assumed Values
P_{11}	The probability of a train being compliant with operation rule (e.g., following 15mph as MAS)	0.95
1- P_{11}	The probability of a train being incompliant with operation rule	0.05
P_{21}	The probability of an on-board computer in I-ETMS system being failed (for "practical" I-ETMS only)	0.0001
P_{22}	The probability of a WIU or radio in I-ETMS system being failed (for "practical" I-ETMS only)	0.0001
1- P_{21} -P_{22}	The probability of no failure in I-ETMS system (for "practical" I-ETMS only)	0.9998
P_{31}	The probability of the train taking the shortest terminal track in terminal	0.1538
1-P_{31}	The probability of the train not taking the shortest terminal track in terminal	0.8462

(b) In ACSES

Parameters	Definition	Assumed Values
P_{11}	The probability of a train being compliant with operation rule (e.g., following 15mph as MAS)	0.95
1- P_{11}	The probability of a train being incompliant with operation rule	0.05
P_{211}	The probability of ACSES system with transponder failure (for "practical" ACSES only)	0.00001
P_{212}	The probability of ACSES system with other component failure(s), such as onboard computer failure, onboard transponder antenna failure (for "practical" ACSES only)	0.0002
1- P_{21}	The probability of no component failure in ACSES (for "practical" ACSES only)	0.99979

Some assumed probabilities are based on experts' experience and a previous study (FRA, 2014). For example, the rate of PTC failure to enforce braking (failures per 1,000 hours of train operation) was assumed to range from 0.0606 to 0.606 in an FRA report (FRA, 2014) that studied PTC risk assessment. But it does not provide direct reference information about PTC component failure. In addition, to the authors' knowledge, quite limited published reports or studies that are publicly accessible discuss PTC component failure or PTC reliability. The probability of a failed on-board computer, WIU, or radio in PTC system would be assumed to have the same magnitudes as the FRA report (2014). In addition, they are also partially based upon railroad expertise. Specifically, it assumes that the probability of an on-board computer failing is 0.0001 per PTC enforcement during train approaching terminal, and the probability of a WIU or radio failing is 0.0001 per PTC enforcement in train approaching terminal as well. In particular, the probability of transponder failure (0.00001) is even lower than other components due to the redundancy provided by the second set. However, to the authors' knowledge, there is no publicly available information about complete PTC component reliability. Railroads and vendors can easily update and achieve their practical operational impact assessment results with their own PTC component reliability data and the assessment tool developed in this report. Moreover, the probability of the train taking the shortest terminal track in the terminal is calculated based on the track lengths in the terminal, which is equal to 0.1538= (2/13).

7.3.2 Statistics of Simulation Results

A 50-year terminal operation in the calculation of total time needed to stop a train safely in the terminal areas is developed and summarized in Table 16. Here it assumes that this terminal has 300 trains entering the terminal every day, which equals 5,475,000 trains in the 50-year operation.

Table 16. Train Operating Time Duration (in Seconds) at Washington Union Station with CE-205 Braking Curve

Scenarios		Mean	Min	CVaR (99.995%)	Max
Terminal without PTC (benchmark)		86.1s	78.1s	93.9s	94.2s
Terminal with ACSES	"Perfect" system without component failure	86.1s	78.1s	95.1s	95.3s
	"Practical" system with probable component failure	86.1s	78.1s	95.1s	95.3s
Terminal with I-ETMS	"Perfect" system without component failure	86.1s	78.1s	95.1s	95.3s
	"Practical" system with probable component failure	86.2s	78.1s	148.2s	196.4s

Note: Train operation duration time indicates the time length that the train spends on terminating tracks, from passing Signal Bridge H to stopping at the targeted point.

Based on the simulation results, the five scenarios (without PTC, with perfect ACSES, with practical ACSES, with perfect I-ETMS, and with practical I-ETMS) have quite similar mean time lengths. But the maximum traveling times in terminal track have an obvious difference. CVaR has primarily been employed in financial engineering (Soleimani et al., 2014), social sciences (Cotter and Dowd, 2006), highway hazardous materials transportation (Toumazis and Kwon, 2016), and recently rail transport of hazardous materials (Hosseini and Verma, 2017) and has been proven as a useful alternative risk measure to capture the "worst-case" or "largest-case" of certain scenarios (Figure 31).

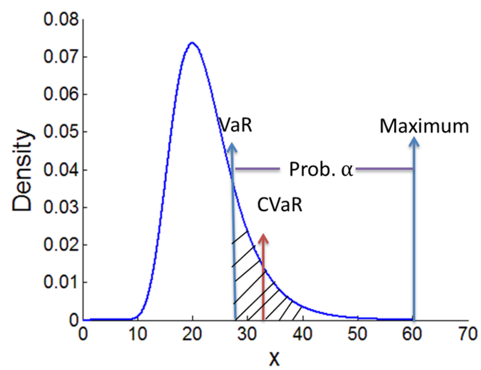


Figure 30. Alternative Measure in CVaR

CVaR is the weighted average of all outcomes exceeding the confidence interval (α-quantile and $\alpha \in (0,1)$) of a dataset sorted from worst to best. For example, CVaR (99 percent) of the time length is the mean (average) of all the numbers of casualties within the longest 1 percent of train operation in terminal tracks in terms of time length. In this report, α is set as 99.995 percent and the CVaR (99.995 percent) represents the average of the longest 0.005 percent of train operating time in terminals (around 550 train operation simulations). According to the results listed in Table 16, the longest 0.005 percent of train operating time in terminals without PTC is 93.9s, which is smaller than that in terminals with practical I-ETMS systems subjected to potential component failure (148.2s). Other scenarios, such as an ACSES system, or a "perfect" I-ETMS system without failure, have similar operation duration (95.1s) with the benchmark.

7.3.3 Mean Time to Train Approaching Delay in Terminals with I-ETMS

With a special interest in the distribution of train approaching durations in the terminals with "practical" I-ETMS that is subject to probable component failure(s), the mean times to train approaching delay is investigated in this section. We found that the probability that the travel time between 100 seconds and 160 seconds for trains within PTC-equipped terminals is 2.28×10^{-6} (Table 17). It indicates that on average, one of 438,000 train movements in terminals (equivalently 4.0-year train operations) needs 100 – 160 seconds. In other words, such train operations occur once every 4.0 years. For more severe delayed train approaching, the probability with over 160 seconds in travel time is only 1.92×10^{-6}. This implies that the occurrence of severely delayed train arrivals is anticipated approximately every five years. Although the likelihood of such "slow" train operation at the terminal is quite small, it can block the path of other trains and delay them from either entering or leaving their tracks. In busy passenger terminals such as Union Station, the delay impacts could be significant, although the occurrence probability is quite low.

The simulation results focus on a single, independent event of the train entering terminal with PTC that is likely to have equipment failure. In practice, WIU failure or radio failure could last for several minutes or even hours and can lead to consistent abnormal train operation status, in which PTC can take the worst-case distance and be delayed from reaching a point within the platform area to be able to discharge passengers. This practical situation can be even more serious for train operations in busy passenger terminals.

Table 17. Distribution of Long-Tail Train Operating Time Length in Terminal with I-ETMS

Frequency Type	Simulated Time Interval	
	[100s, 160s]	[160s, +∞]
Frequency per train operation	2.28×10^{-6} /train operations	1.92×10^{-6} /train operations
Frequency per year	0.25 /year	0.22 /year
Mean time to such time duration	4.0 years	4.8 years

Note: Here it assumes that this terminal has 300 trains approaching the terminal per day, 109,500 trains per year.

7.3.4 Sensitivity Analysis of PTC Component Failure

In this section, a preliminary sensitivity analysis of PTC component failure was conducted for two reasons:

a) To account for the uncertainties and variations of PTC component failure probabilities, under a variety of vendors offering nationwide PTC components

b) To understand how changes in practice or failure prevention technology mitigation affect the overall operational impact and terminal capacity.

Considering the relatively significant impact of system component failure in I-ETMS, this section focuses on the terminal with “practical” I-ETMS only. The previous case study assumed that both the probability of an onboard computer in I-ETMS system being failed and the probability of a WIU failure and/or radio failure in I-ETMS system being failed is 0.0001, and the probability of no failure in I-ETMS system is then 0.9998. In addition to the 0.0001 in the previous case study, this section also considers 0.00001, 0.00002, 0.00005, 0.0002, 0.0005, 0.001, 0.01, and 0.1. The distributions of train operating time duration at terminals are summarized in Figure 32.

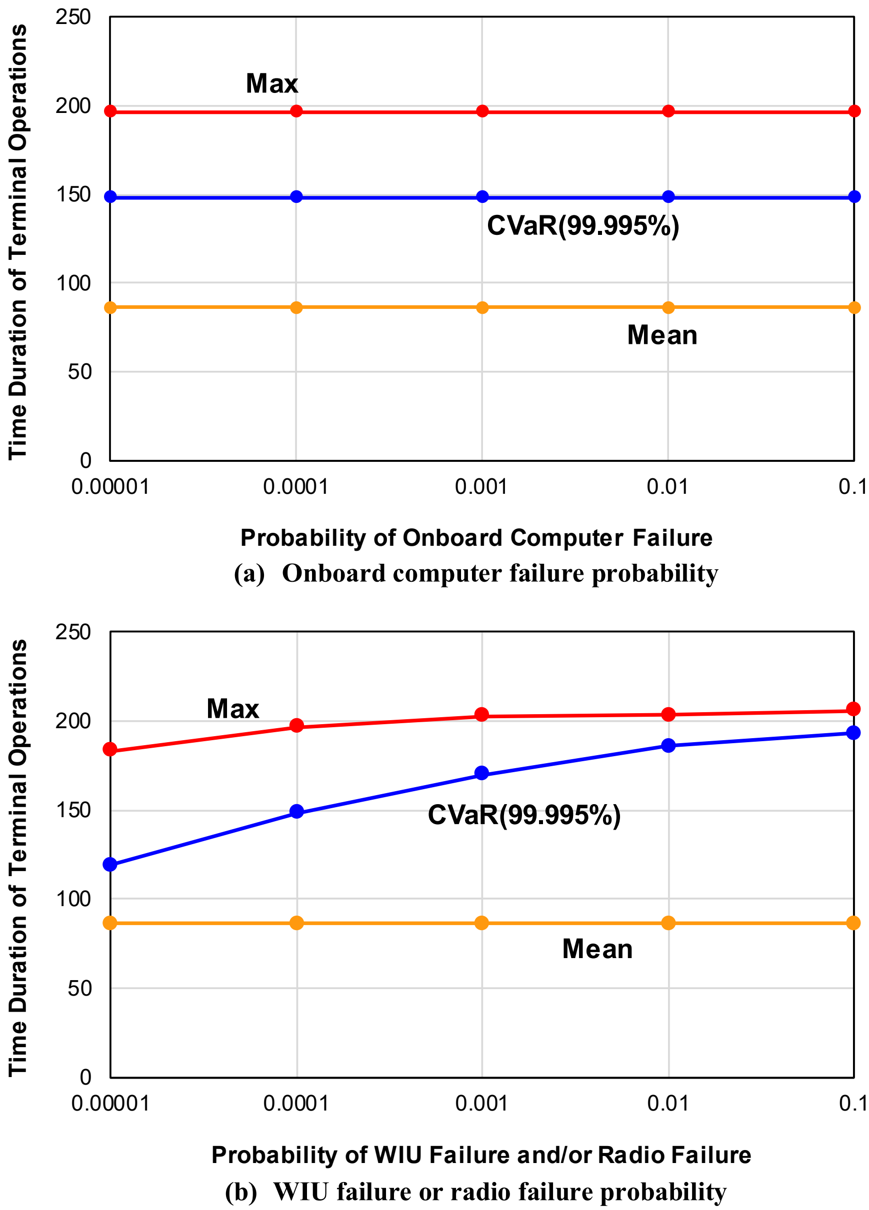


Figure 31. Sensitivity Analysis for Train Operating Duration (in Seconds) Affected by a) Onboard Computer Failure Probability; b) WIU Failure or Radio Failure Probability

For I-ETMS with onboard computer failure (Figure 32a), the three measurements (e.g., mean, CVaR, and max) remain almost constant while the probability of onboard computer failure changes between 0.00001 and 0.1. However, considering the major effect is from the probability of WIU failure and/or radio failure, this section concentrates on the sensitivity analysis of train terminal operating time duration with varying probability of WIU failure and/or radio failure. According to simulation results (Figure 32b), the probability of WIU failure and/or radio failure does not have an impact on the mean value of train operating time duration, while it does have some effect on the "worst-case" measures (e.g., CVaR and Max). For example, when the probability of WIU failure and/or radio failure is only 0.001 (10 times of original case), the CVaR (99.995 percent) and maximum value would increase 14.6 percent $(\frac{169.8-148.2}{148.2})$ and 3.3 percent $(\frac{202.9-196.4}{196.4})$, respectively. While for the probability of WIU failure and/or radio failure being 0.00001 (0.1 times of original case), the CVaR (99.995 percent) and maximum value would decrease 19.6 percent $(\frac{119.1-148.2}{148.2})$ and 6.7 percent $(\frac{183.2-196.4}{196.4})$, respectively. While the probability of WIU failure and/or radio failure is assumed to be 0.00001, values of CVaR (99.995 percent) are quite close to the value of that without PTC systems. It indicates that even for the worst 110 train operating time durations, their average value is quite close to the benchmark and the operational impact would be extremely minor compared with the original case study. However, the maximum value for any value of probability of WIU failure or radio failure is still quite large (over 160 seconds). To further study these most severe cases, the mean time to frequency is also investigated here.

If the "moderate delay" is defined as train terminal operation duration between 100 and 160 seconds and the "severe delay" is defined as train terminal operation duration over 160 seconds, Table 18 summarizes the distributions of mean time to these delayed train terminal operations under different probabilities of WIU failure or radio failure.

Table 18. Train Operating Time Duration (in Seconds) under Varying Probabilities of WIU Failure or Radio Failure

Probability of WIU failure or radio failure	Mean Value	CVaR (99.995%)	Maximum value	Mean time to train delay	
				Moderate delay [100s, 160s]	Severe delay [160s, +∞]
0.1	86.4s	192.7	206.1	0.004 year	0.005 year
0.01	86.2s	185.5	203.5	0.03 year	0.07 year
0.001	86.2s	169.6	203.1	0.4 year	0.5 year
0.0005	86.2s	163.4	197.4	0.8 year	1.1 year
0.0002	86.2s	158.5	196.0	2.1 years	2.5 years
0.0001	86.2s	148.2s	196.4	4.0 years	4.8 years
0.00005	86.2s	131.8	191.4	8.4 years	8.9 years
0.00002	86.2s	121.9	188.6	19.1 years	23.8 years
0.00001	86.1s	119.3	182.7	35.7 years	44.4 years
Terminal without PTC system (benchmark)	86.1s	93.9s	94.2s	-	-

When the probability of WIU failure or radio failure is 0.001 or even higher, the mean time to either moderate delay or severe delay is lower than 1 year, which is significantly more frequent than the original case (probability = 0.0001). In addition, as the probability of WIU failure or radio failure is reduced to 0.00001, the mean time to either moderate delay or severe delay would be measured in decades – a rare event. It highlights the lower probability of WIU failure or radio failure, the longer mean time to train delayed operations at terminals with the proposed PTC system. In other words, it underscores that the probability of WIU failure or radio failure distinctly influences the mean time to train delays. A lower failure probability, indicating higher reliability, would essentially result in rarer train delay events and significantly diminish adverse operational impacts.

7.4 Summary of Operational Impact Assessment

This section provides a scenario-specific operational impact assessment study for PTC enforcement during train operations under restricted speeds. Negligible operational impacts from the "perfect" PTC system enforcement at stub-end terminals may potentially result from the low probability of noncompliant train operations, rare component failure, and the insignificant difference between engineer-induced braking curve and PTC-induced braking curve. In passenger terminal stations, train speed is low due to restricted speed rules. Thus, the impact of PTC braking curve characteristics would be negligible during train operations at terminus stations.

In real-world PTC systems, component failure may occur, although it is a rare event. In ACSES and I-ETMS systems, PTC component failure would cut off PTC function and leave the engineer in command of train movement under the ConOps, except for the failure of a WIU and/or a failed radio. The I-ETMS system with a failed WIU and/or radio can still enforce restricted speeds and prevent the train from hitting the bumping post. However, since a WIU and radio are employed to monitor and transmit the position information of the switches, the failure would result in missing the planned route and the exact distance to bumping post. As a result, it would take the worst-case distance, or the shortest distance, to the bumping post as the braking curve calculation. This can lead to a stopping enforcement well short of the targeted point. In general, the train would be delayed from reaching a point within the platform area to be able to discharge passengers. Besides, this delay increases the time that the train would occupy individual track segments and the end of the train would be blocking the path of other trains, delaying them from either entering or leaving their tracks, likely leading to congestion. In busy passenger terminals such as Union Station or during rush hour periods, the delay impacts could be relatively significant. However, simulation analysis demonstrates that the adverse impact could not be significant to terminal operation in general, since WIU/radio failure resulting in taking the non-shortest track is such a rare event. Stopping well short of the targeted point requires the simultaneous occurrence of at least three events: noncompliant train movement, WIU/radio failure, and taking a longer terminating track. Thus, the probability of all three events occurring is extremely low. Furthermore, the sensitivity analysis indicates that PTC with very high reliability (low component failure probability) would notably reduce the occurrence of train delay and minimize adverse operational impacts.

8. Field Testing

This section demonstrates in-field testing plans for the proposed ConOps, in which ACSES-type PTC systems and I-ETMS-type PTC systems are implemented at passenger terminal stations.

The purpose of this section is to describe the procedures and instructions to be followed to demonstrate the feasibility of positive stop enforcement in an ACSES-equipped or I-ETMS-equipped passenger terminal to prevent a PTC-equipped train from hitting a bumping post at the end of a platform track. In the field test plan, a train equipped with one locomotive and at least one passenger coach would be tested on platform tracks in a selected passenger terminal. There are three major testing components: test equipment, the test track, and recorded information for each test sequence. First, in terms of equipment of the ACSES system, a traffic cone will be placed on the track to simulate a bumping post. In the ACSES system, two sets of transponders are programmed to require a positive stop within a specified distance and mounted to the cross ties at specified positions. In the I-ETMS system, track mapping and sufficient WIU slots should be guaranteed in the equipment preparation stage. Secondly, a yard track will be used to test the feasibility of this exercise at the beginning. Upon successfully completing the test multiple times, a series of tests will also be performed on the studied platform track. Thirdly, each test run should record the distance from the head end of the test train to the traffic cone. In particular, the ACSES system should also record the information on the ACSES display as it passes the first and second transponder sets. Overall, the field tests presented in this section, along with previous work in benefit-cost analysis and operational impact assessment, can contribute to an assessment of the proposed PTC implementation at stub-end terminals in the U.S. to prevent end-of-track collisions effectively and efficiently.

8.1 Field Test Plan for End-of-Track Collision Prevention with ACSES

8.1.1 Preparation and Configuration of Field-Testing Plan in ACSES-Type Terminal

8.1.1.1 Test Equipment

The test must have two sets of transponders programmed to require a positive stop within a specified distance. These transponders will be placed on the track (between the rails) and mounted to the cross ties at specified positions. A traffic cone will be placed on the track to simulate a bumping post. An ACSES-equipped locomotive with at least one passenger coach will be used as the test train.

In addition to the incremental hardware, other devices are also needed. In particular, a measuring device (measuring wheel) will be used to measure distances for the placement of transponders and for measuring the distance from the stopping point of the test train to the traffic cone used to simulate a bumping post. A laptop computer will be used to download test data from the onboard computer (OBC).

8.1.1.2 Participants

Participants during the testing shall include Amtrak signal department personnel, a locomotive engineer, a road foreman and members of the PTC Restricted Speed Enforcement Research team. The Amtrak employee in charge shall conduct a safety briefing prior to the beginning of the test. All testing shall be coordinated with the dispatcher or yardmaster in charge of the track being used for testing.

8.1.1.3 Test Track

A platform track at Washington Union Station will be selected for the test. The track will be measured, and the location of transponders will be selected. Using the measurements of the platform track and the transponder locations, a yard track in Amtrak's Ivy City Yard will be used to test the feasibility of this exercise before testing on the actual platform track.

The yard track will simulate the actual platform track for the first test. The track will be marked to show the beginning and end of the platform. Transponders will be placed exactly as they would be placed on the platform track. A traffic cone will simulate the location of the bumping post.

By first testing on a yard track, it will be proven that the train will be stopped before contacting the bumping post. If the train contacts the traffic cone, adjustments can be made to ensure that the train will be stopped prior to contacting the bumping post. Upon successfully completing the test multiple times, any adjustments made will also be made on the platform track. A series of tests will then be made on the actual platform track with the results recorded for each test. The test track shall provide enough braking distance for a stop enforcement from 20 mph (restricted speed) to stop the train after reading the first transponder set.

8.1.1.4 Test Track Configuration in Yard Track

The yard track will be configured as similarly as possible to the platform track chosen for the test in the terminal. The track will be marked to show where the platform would be and a traffic cone will simulate the bumping post. The first transponder set will be installed at the entering end of the simulated platform, exactly as it would be placed on the actual platform track. The second transponder set will be placed midway between the first transponder set and the traffic cone at the same distance from the first set, as would be done on the actual platform track.

The first transponder set will be programmed to require a positive stop just prior to hitting the traffic cone. The second transponder set will be programmed with a new distance, to require a positive stop from the maximum timetable speed for the test track to a point short of the traffic cone. The yard test track will be inaccessible by other trains during the testing.

8.1.1.5 Test Track Configuration in Platform Track

Once the testing has been successfully completed on the yard track, the test transponders will be installed on the platform track in the same manner as the yard track (Figure 33). The tests will be repeated for the platform track in the same manner as the yard track, with the results recorded for each test. The platform track will be out of service for revenue trains and the entrance to the test track will be blocked to all revenue trains by the dispatcher or yardmaster. In particular, the CE-205 braking curve (Figure 28) that is widely used by Amtrak and commuter railroads is cited as one reference in the calculation of braking distance.

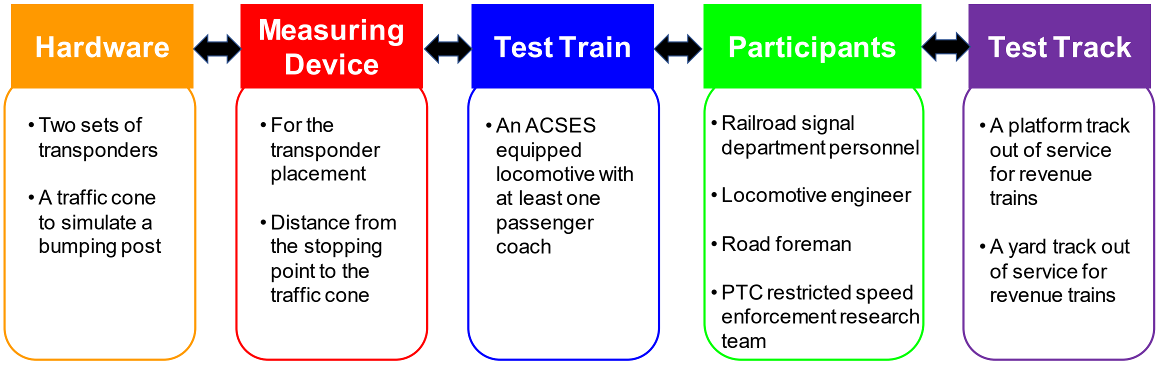


Figure 32. Test Environment in ACSES Terminal

8.1.2 Field Testing in ACSES-Type Terminal

8.1.2.1 First Test Sequence

The test train will enter the test track at restricted speed (20 mph) with the onboard ACSES system but out of ACSES territory mode. As the test train passes the first transponder set, the ACSES system should activate and display a time to penalty. The engineer shall not apply the brake to force the system to enforce a positive stop before reaching or hitting the traffic cone. The ACSES system should apply the brake and enforce a positive stop (Figure 34). Once the train comes to a full stop, the distance between the head end of the test train and the traffic cone should be measured and recorded.

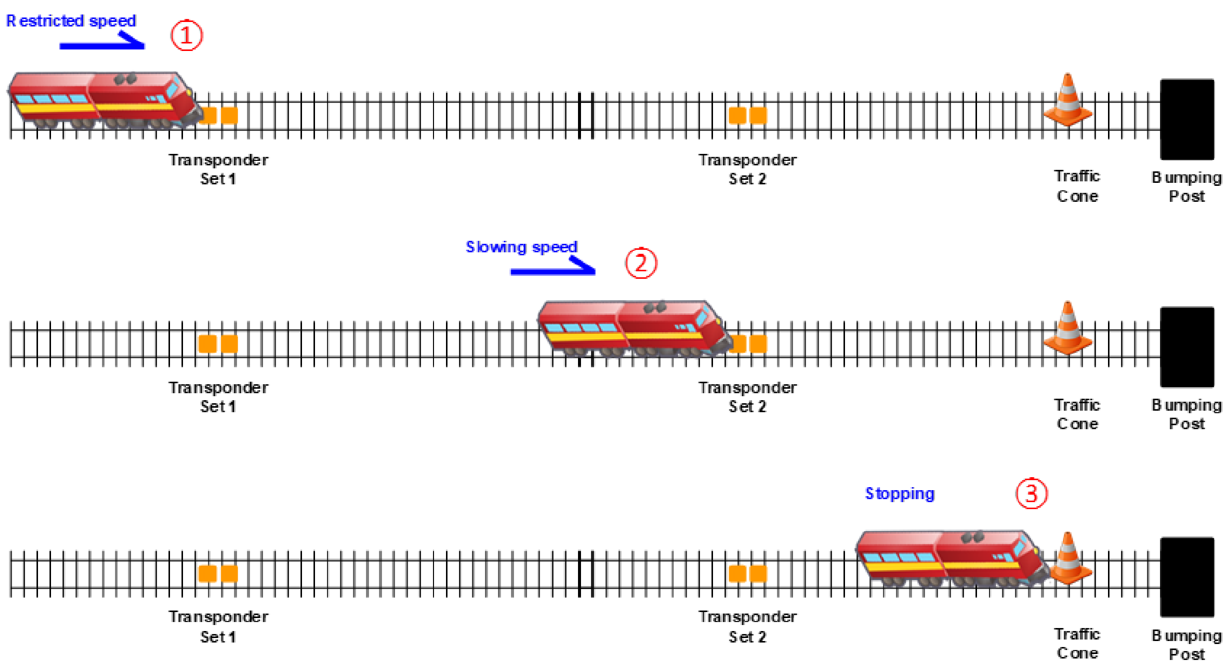


Figure 33. Illustrations of First Test Sequence with ACSES

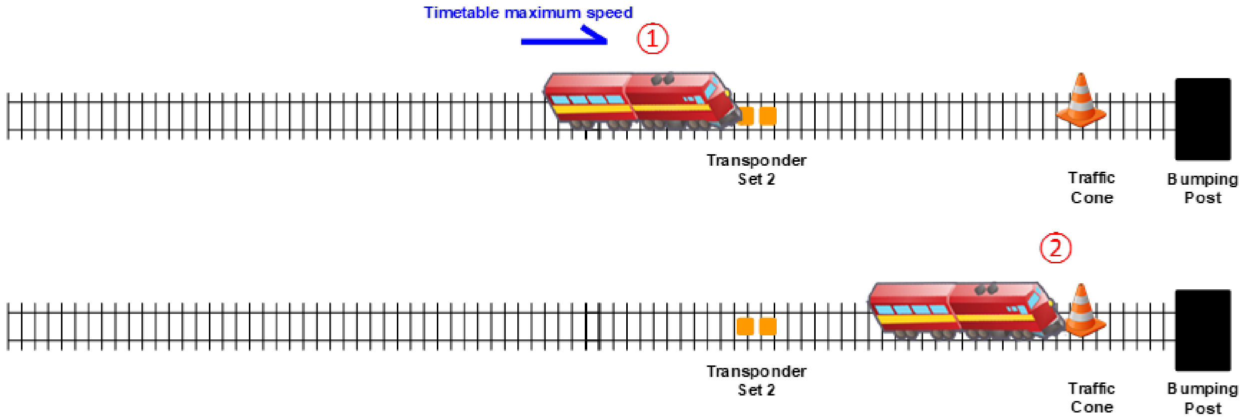


Figure 34. Illustrations of Second Test Sequence with ACSES

The above procedure should be repeated several times with the stopping distance recorded each time. The test results should be consistent within a few feet. For each test run, the following shall be recorded:

- The information on the ACSES display as it passes the first transponder set
- The information on the ACSES display as it passes the second transponder set
- The distance from the head end of the test train to the traffic cone for each test run

8.1.2.2 Second Test Sequence

The first transponder set will be covered or removed from the test track. The test train will enter the test track at the timetable maximum speed. As the train passes over the first transponder set (covered or missing), the ACSES system should not activate. As the test train passes over the second transponder set, the system should activate and begin a countdown to enforcement. When the systems enforce a positive stop, the distance between the train and the traffic cone will be measured (Figure 35). If the train passes the traffic cone, the researcher will measure the distance the train traveled after passing the cone. This test must be done on the yard test track prior to performing the test on the platform track. If the second transponder set does not provide adequate braking distance, the position of the second transponder set should be adjusted to provide the required braking distance. The same adjustment will be made to the position of the second transponder set on the platform track. The test should be repeated at least one more time and a comparison should be made between the data recorded for each test run.

8.2 Field Test Plan for End-of-Track Collision Prevention with I-ETMS

8.2.1 Preparation and Configuration of Field Testing Plan in I-ETMS-Type Terminal

8.2.1.1 Test Equipment

The test requires a WIU to monitor all the switches within the terminal, providing routing information to the on-board computer and track mapping to obtain the distance between a point where the test train enters the terminal and the end of the track (bumping post). A traffic cone will be placed on the track to simulate a bumping post. An I-ETMS-equipped locomotive with at least one passenger coach will be used as the test train. A measuring device (measuring wheel) will be used to measure the distance from the stopping point of the test train to the traffic cone used to simulate a bumping post. A laptop computer will be used to download test data from the on-board computer (OBC).

8.2.1.2 Participants

Participants during the testing will include Amtrak signal department personnel, a locomotive engineer, a road foreman, and members of the PTC Restricted Speed Enforcement Research team. The Amtrak employee in charge will conduct a safety briefing prior to the beginning of the test. All testing will be coordinated with the dispatcher or yardmaster in charge of the track being used for testing.

8.2.1.3 Test Track Configuration in Yard Track

A platform track at Washington Union Station will be selected for the test. The track will be mapped and a WIU will be installed with input of switch positions. Track mapping is conducted to identify the location of switches and the distances from the terminal entrance to each bumping post. This information is stored in the subdivision track database file. When an I-ETMS locomotive initializes, the engineer must enter the route that the train will take. This information is sent to the BOS, which will then check if the database is already on the locomotive, and if so, that the database is the correct version. Using a similar mapping survey of the platform track, a yard track in Amtrak's Ivy City Yard will be used to test the feasibility of this exercise before testing on the actual platform track. The yard track will be configured as similarly as possible to the platform track chosen for the test in the terminal. The track will be marked to show where the platform would be, and a traffic cone will simulate the bumping post. A separate test database with mapping will be provided for this series of tests.

By first testing on a yard track, it will be proven that the train will be stopped before contacting the bumping post. If the train contacts the traffic cone, adjustments can be made to ensure that the train will be stopped prior to contacting the bumping post. Upon successfully completing the test multiple times, any adjustments made will also be made on the platform track. A series of tests will then be made on the actual platform track with the results recorded for each test. The test track should provide enough braking distance for a stop enforcement from 20 mph to stop the train on the test track. The yard test track will be inaccessible to other trains during the testing.

8.2.1.4 Test Track Configuration in Platform Track

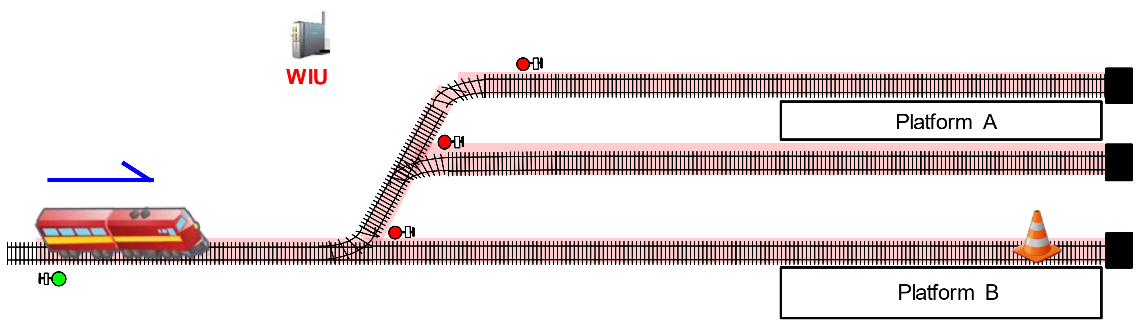
Once the testing has been successfully completed on the yard track, track mapping should be conducted and validated on the platform track and updated to the subdivision track database file and BOS in the same manner as the yard track. The tests will be repeated for the platform track in the same manner as the yard track, with the results being recorded for each test. The platform track will be out of service for revenue trains and the entrance to the test track will be blocked to all revenue trains by the dispatcher or yardmaster. In particular, the CE-205 braking curve (Figure 28) that is widely used by Amtrak and commuter railroads is cited as a reference in the calculation of braking distance.

8.2.2 Field Testing in I-ETMS-Type Terminal

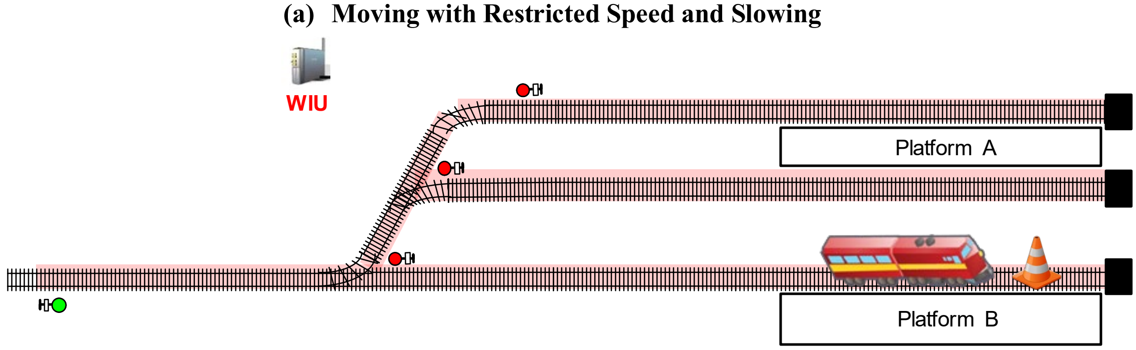
The test train will enter the test track at restricted speed (e.g., 15 mph) with the onboard I-ETMS system but with deactivated GPS mode. With the test train approaching the terminating track, the engineer will not apply the brake to force the system to enforce a positive stop before reaching or hitting the traffic cone. The I-ETMS system should apply the brake and enforce a positive stop (Figure 36). Once the train comes to a full stop, the distance between the head end of the test train and the traffic cone should be measured and recorded.

The above procedure should be repeated several times, with the stopping distance recorded each time. The test results should be consistent within a few feet. For each test run, the following shall be recorded:

- The I-ETMS-equipped test train speed entering the terminating track
- The distance from the head end of the test train to the traffic cone for each test run



(a) Moving with Restricted Speed and Slowing



(b) Stopping

Figure 35. Illustrations of Field Test with I-ETMS

9. Conclusion

The objective of this research was to study the restricted-speed train safety risk and effective accident prevention strategies with the implementation of PTC systems. The quantitative analysis of restricted-speed accident frequency, severity, and risk found that the rate of restricted-speed train accidents has no significant change since 2000, while the overall train accident rate had declined substantially. The micro-level study with FTA showed that PTC designed for human error mitigation was one primary restricted-speed accident risk prevention strategy. In particular, the potential implementation of PTC systems at restricted-speed train operations was proposed to improve the safety level of train operations at restricted speeds via automatically stopping a train if the engineer is negligent or disengaged.

Train movements at terminus stations are one common scenario of restricted-speed operations. This research analyzed the safety statistics of end-of-track collisions, then developed both FTA and STAMP to understand the causes and contributing factors of end-of-track collisions. To assess the potential implementation of PTC for passenger terminals, both benefit-cost analysis, including incremental costs and safety benefits, and operational impacts were evaluated quantitatively. The benefit-cost analysis showed the safety benefits from end-of-track collision prevention may exceed the installation costs and maintenance costs for a 20-year service life. Specifically, the annualized NPV (benefits minus costs) was around $800,000 (2017 dollars, 7 percent discount rate) or $1.3 million (2017 dollars, 3 percent discount rate). The BCR was around 2.2 under a 7 percent discount rate or 2.5 under a 3 percent discount rate, approximately. In terms of operating capacity, the Monte Carlo-simulation-based analytical results indicated that the operational impact in PTC enforcement should be negligible, except for the rare occurrence of WIU failure or radio failure in I-ETMS-type PTC system that would potentially result in a stop well short of the targeted point and delay both onboard passengers and inbound/outbound trains.

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Appendix A. Scenario-Specific Concept of Operations

Table A1 provide a summary of the proposed modifications for each restricted-speed scenario. Major types of equipment are covered in this table, which excludes software in the back office and locomotives.

Table A1. Equipment Needed in Proposed Modifications (Excluding Software)

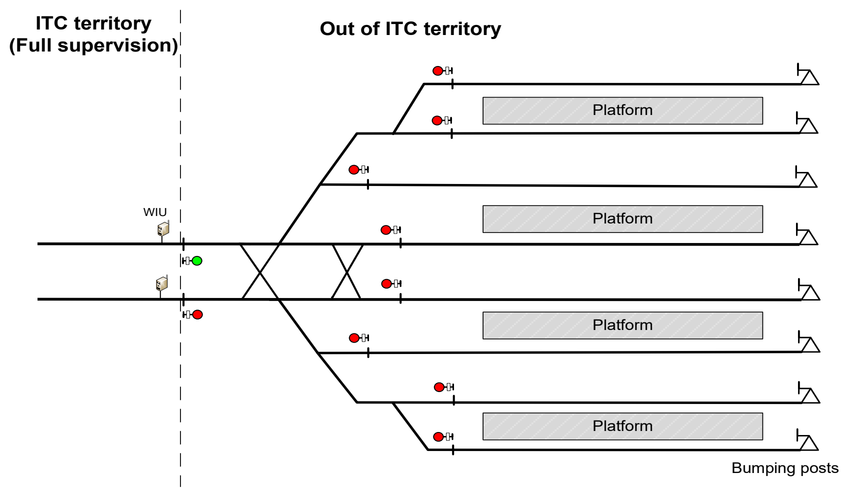
Scenarios	I-ETMS	ACSES
Stub-end terminal	Station track mapping, WIU	Transponders
Through terminal	Station track mapping	Nothing else needed
Non-signaled siding	track mapping, WIUs (hand switch only)	Nothing else needed
Interlocking	Nothing else needed	Nothing else needed
ABS – Alarmed defect detector	Nothing else needed	Nothing else needed
ABS – Occupied block ahead	Nothing else needed	Nothing else needed
ABS – Misaligned switch	Nothing else needed	Nothing else needed
CTC	Nothing else needed	Nothing else needed
Yard limits	Track mapping, WIU (optional)	Nothing else needed

Apart from the previously noted equipment, rear-end protection is also needed in specific scenarios, including instances of interlocking and when encountering an occupied block ahead in ABS. To prevent a rear-end collision, the following train would have to know the limits of movement based on the position of the rear of the train ahead. Rear-end protection would require a device, such as GPS, on the rear of the train with some means to stop the following train before a collision occurs. This would be a major upgrade to the current PTC system. PTC types in current operations do not identify the position of the end of trains nor do they confirm the integrity of trains. As such, there is no way to determine where the stopping point should be for trains operating within an occupied block. This type of train tracking is required for standalone systems and would require an extensive re-design of existing PTC systems that is considered outside the scope of this report. Otherwise, in blocks known to be occupied, trains would be enforced to a stop at the entrance of the block and await instructions before proceeding.

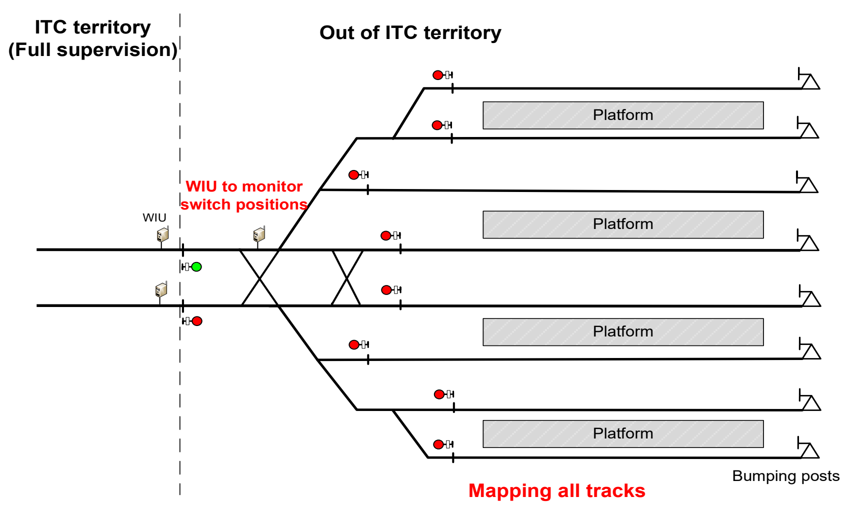
Stub-End Terminal

Figure A1 shows a stub-end terminal. There may be no specific information as to the status of the switches. This is particularly true in areas of MTEA. With an I-ETMS system, station tracks could be mapped (Figure A1b) to obtain exact distances between the end of the bumping posts and a point where the train was able to obtain a good GPS signal. Restricted speed would be enforced if a train occupied a terminal track. For the system to know how far to allow the train to travel before enforcing a positive stop, it would have to know the position of every switch in the route to determine the distance to the bumping post. This would require the installation of a WIU to monitor the position of the switches. The train would query the WIU via its data radio to obtain this information. Once the route was determined the system would know the allowable distance that it could travel until it reached the bumping post. The I-ETMS system would then calculate a braking profile based on the current speed of the train and the distance to the bumping post and enforce a positive stop short of the stop target.

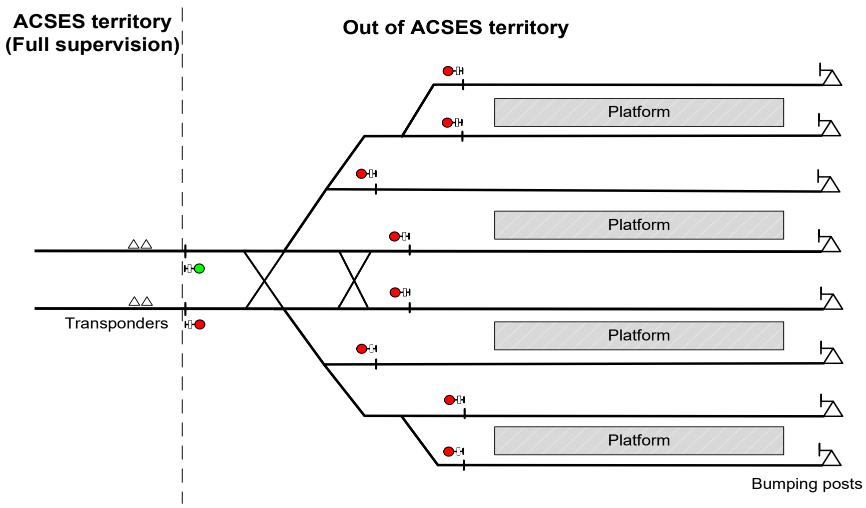
With ACSES, the ATC system can enforce the train speeds to the wayside signal indication (such as restricted speed indication). The proposed solution is to divide the terminal into two zones, as shown in Figure A1d. As the train reaches the end of full ACSES territory the last transponder set tells the onboard ACSES system that it has entered "Out of ACSES Territory" (Zone 1). The second zone begins at the entering end of each platform. The first transponder set (T1) makes the system re-enter ACSES territory and provides PTS information targeting the end of the platform track or bumping post as the stop target. This transponder set also provides linking distance information to the next transponder set (T2). The first transponder set needs to be located at a distance greater or equal to the braking distance needed to stop the train. The second transponder set (T2) provides redundancy to the first set and better stopping accuracy. This transponder set provides a PTS with the distance to the bumping post and allow the train to safely stop short of the bumping post or end-of-track (Figure A1d).



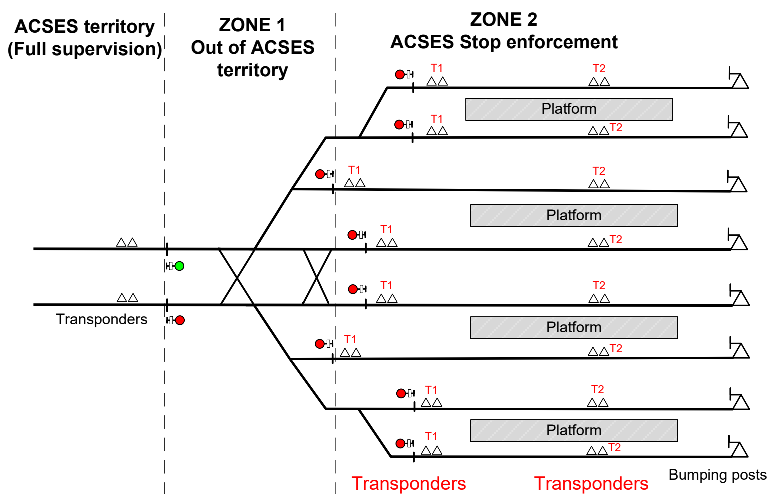
(a) Without modifications in I-ETMS



(b) With modifications in I-ETMS



(c) Without modifications in ACSES

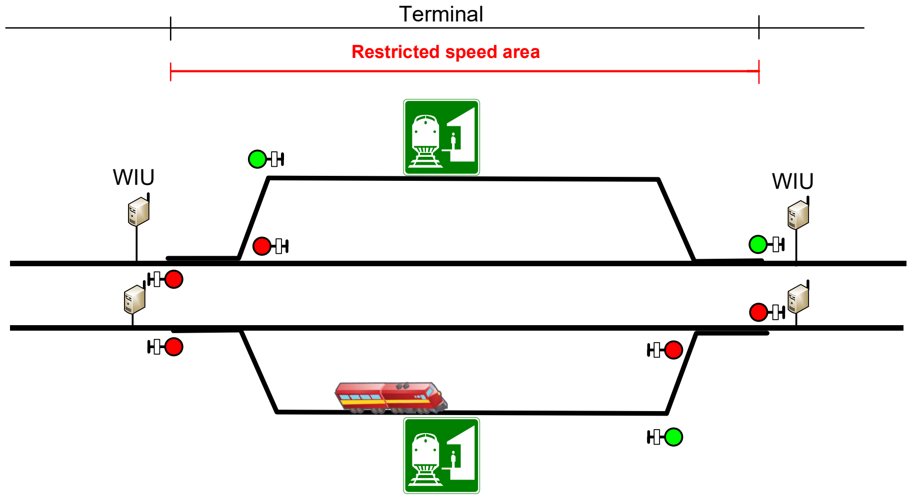


(d) With modifications in ACSES

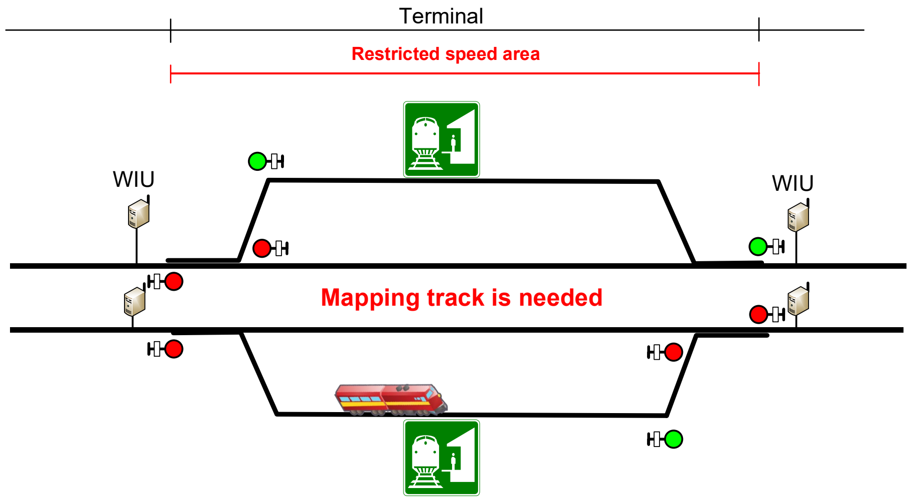
Figure A1. Stub End Terminal a) Without Modifications in I-ETMS; b) With Modifications in I-ETMS; c) Without Modifications in ACSES; d) With Modifications in ACSES

Through Terminal

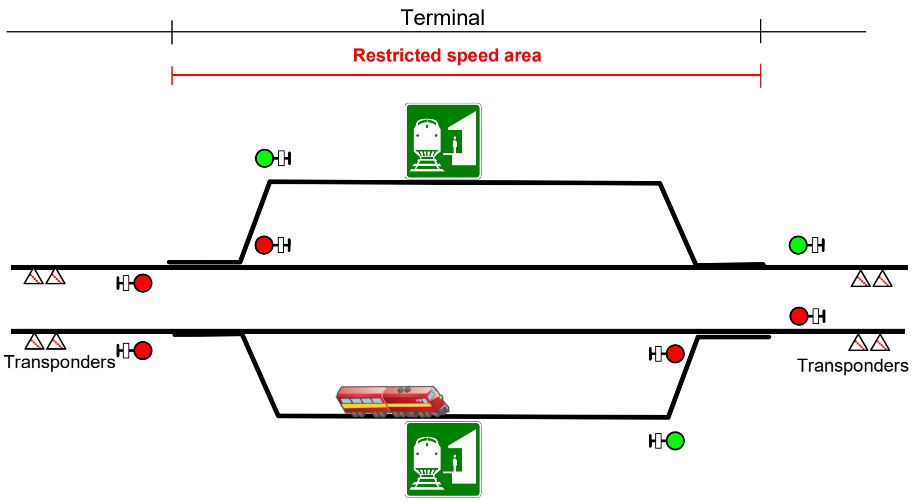
In Figure A2a, the station tracks are non-PTC tracks. With an I-ETMS system, these tracks could be mapped, and the PTC system would enforce restricted speed as long as the train occupied either station track (Figure A2b). With ACSES system transponders at each end of the main tracks would be used to cut in/out the ACSES system in almost all terminal areas (Figure A2c). Then the ATC system will be active and enforce restricted speed within terminal tracks. Thus, no additional hardware equipment is needed here.



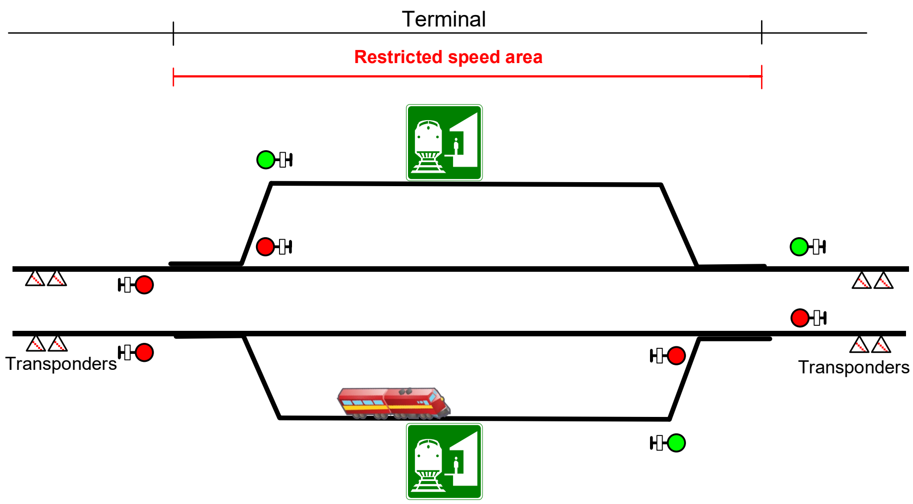
(a) Without modifications in I-ETMS



(b) With modifications in I-ETMS



(c) Without modifications in ACSES

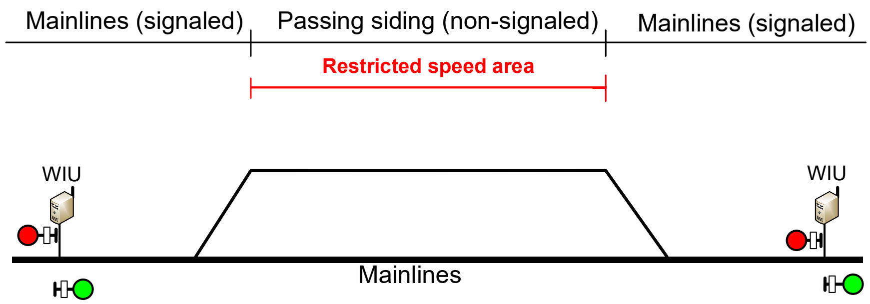


(d) With modifications in ACSES

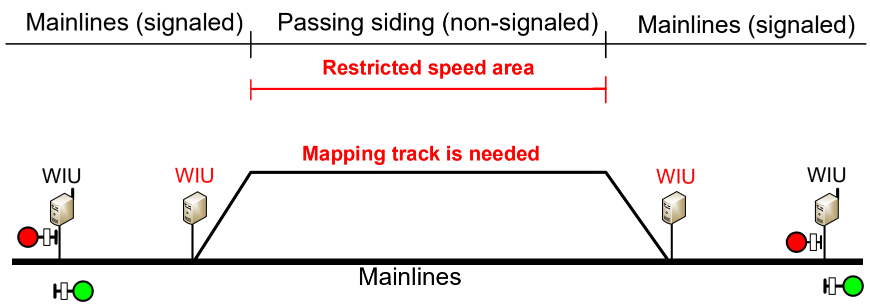
Figure A2. Scenarios in Through Terminal a) Without Modifications in I-ETMS; b) With Modifications in I-ETMS; c) Without Modifications in ACSES; d) With Modifications in ACSES

Non-Signaled Siding

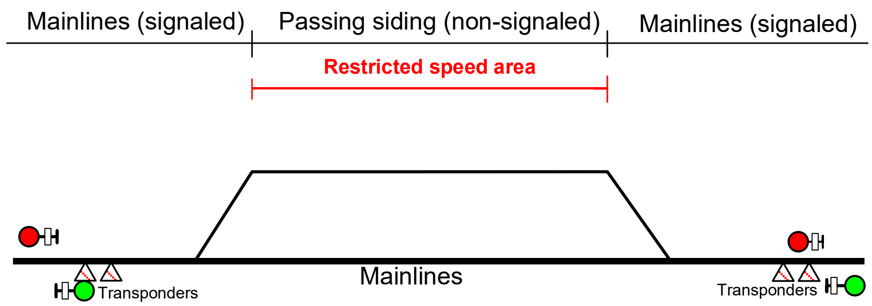
In the case of a siding track with hand-operated switches, tracks could be mapped, and the I-ETMS system would remain engaged. Restricted speed would be enforced while the train occupies the mapped track. A WIU would also be needed at a hand-operated switch location to monitor the switch conditions (Figure A3b). In the case of an ACSES system, transponders would be existing in PTC system. The ATC system would enforce the restricted speed and no additional hardware would be necessary in speed enforcement (Figure A3d). In addition, existing transponders are used to prevent the train from entering the main track without authorization.



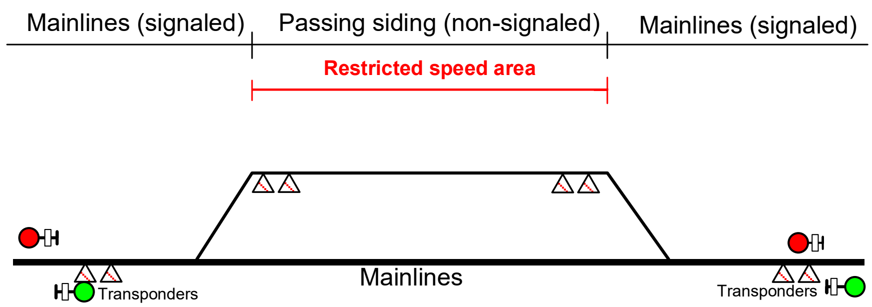
(a) Without modifications in I-ETMS



(b) With modifications in I-ETMS



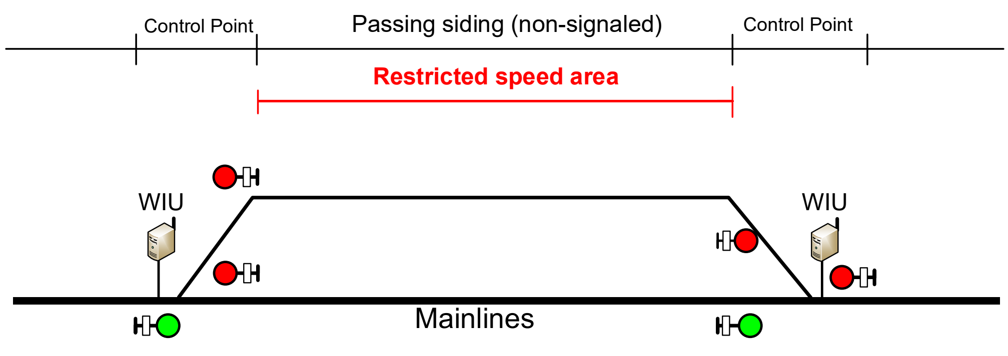
(c) Without modifications in ACSES



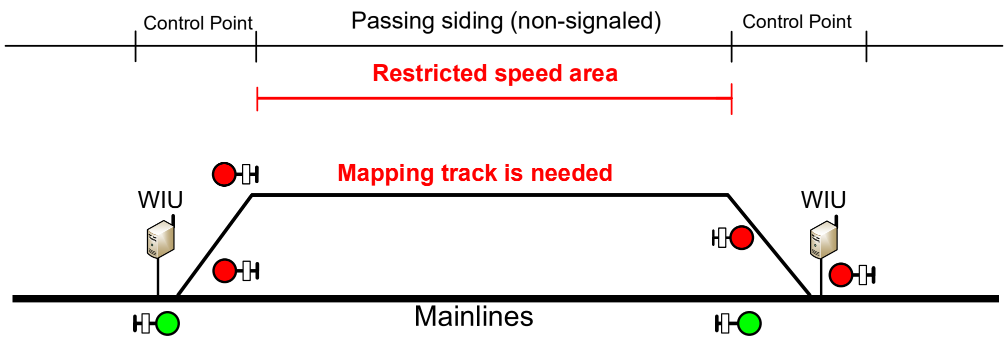
(d) With modifications in ACSES

Figure A3. Scenarios in Non-Signaled Siding with Hand-Operated Switch a) Without Modifications in I-ETMS; b) With Modifications in I-ETMS; c) Without Modifications in ACSES; d) With Modifications in ACSES

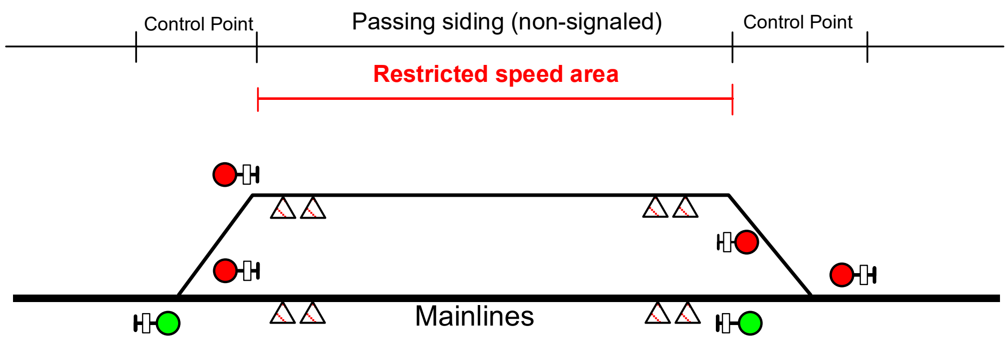
In the case of a siding track with power operated switches, it could also be mapped and the PTC system would remain engaged. Restricted speed would be enforced while the train occupies the mapped track. A WIU would already be installed at a power-operated switch location and there would be no need for additional WIUs at control points, in which absolute signals are controlled by a control operator. (Figure A4b). The ATC system would enforce the restricted speed and no additional hardware would be necessary in speed enforcement (Figure A4d).



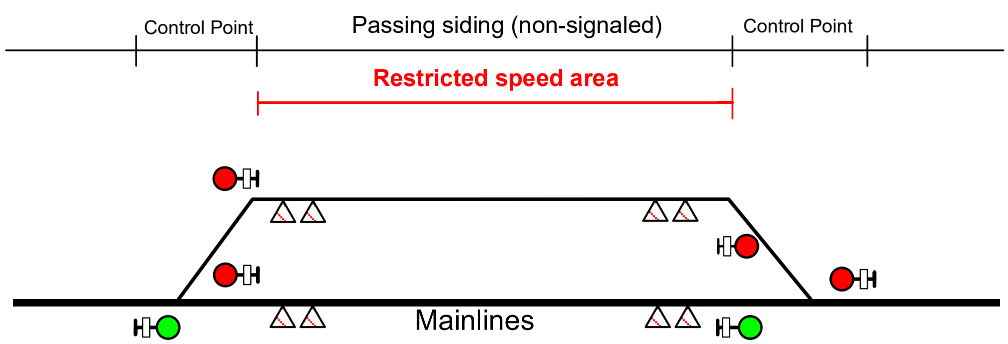
(a) Without modifications in I-ETMS



(b) With modifications in I-ETMS



(c) Without modifications in ACSES

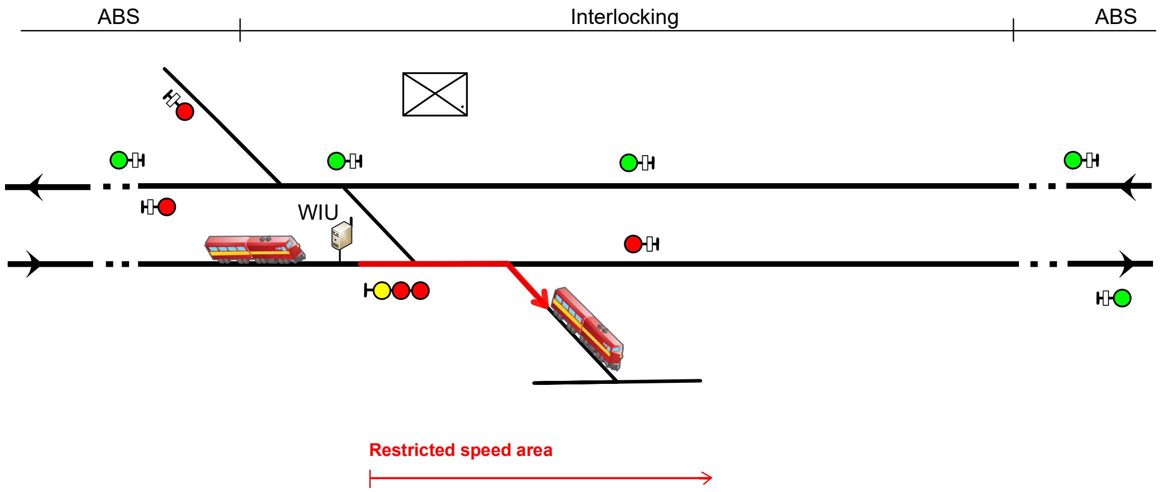


(d) With modifications in ACSES

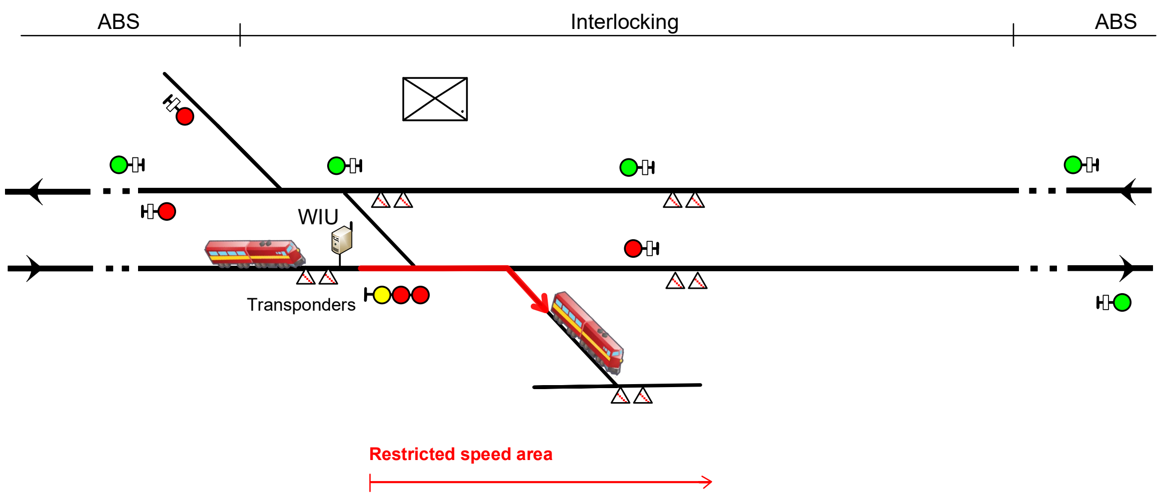
Figure A4. Scenarios in Non-Signaled Siding with Power-Operated Switch a)Without Modifications in I-ETMS; b)With Modifications in I-ETMS; c)Without Modifications in ACSES; d)With Modifications in ACSES

Interlocking

Interlocking is an interconnection of signals and signal appliances such that their movements must succeed each other in a predetermined sequence (NORAC, 2011). In the interlocking rules, signals cannot be displayed simultaneously on conflicting routes. Figure A5 shows a situation where both trains may have restricted speed enforcement and the Call-On function enabled. In interlocking, power-operated switches are used and WIUs would already be installed. An I-ETMS system would require no additional hardware to enforce restricted speed into the yard tracks (Figure A5a). An ACSES system with ATC would enforce restricted speed into the yard or non-PTC track due to restricted speed in the cab. WIUs and transponders that have been installed can provide necessary information ahead, such as cutting ACSES out/in. Thus, no additional equipment is needed in either I-ETMS or ACSES.



(a) I-ETMS (no modifications needed)

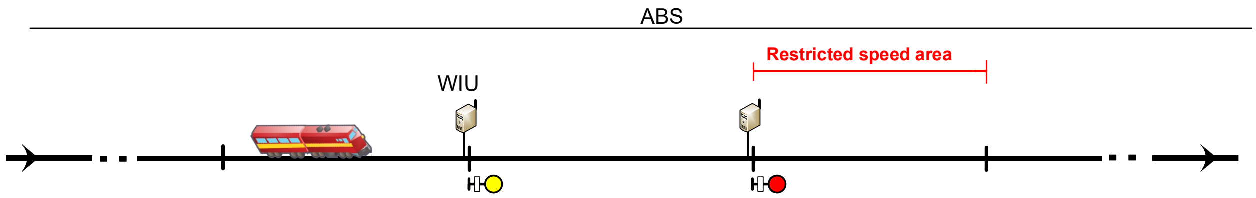


(b) ACSES (no modifications needed)

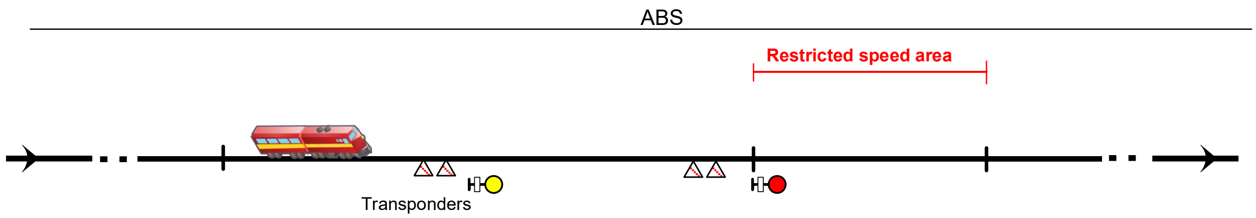
Figure A5. Restricted-Speed Scenarios in Interlocking with Occupied Yard in a) I-ETMS; b) ACSES

ABS – Defect Detector Alarmed

In this scenario the train is slowed down by the signal system at the APPROACH signal (Figure A6). A STOP signal would be displayed at the entrance of the block where the defect was detected. The defect detector could be a slide fence detector, high-water detector, or fire detector for a wooden deck bridge or a broken rail. In such cases the defect detector or broken rail would cause the signal governing the entrance to block to display STOP. The signal for a train approaching the stop signal would display 'APPROACH,' and the PTC system would enforce a speed reduction, enabling the train to safely come to a stop at the signal. The PTC system should enforce the restricted speed as the train passes the red signal. The restricted speed would be enforced until the next signal. In an I-ETMS system, WIU is needed to get information about the status of the signal while approaching signal. 49 CFR 236 Subpart I requires that defect detectors integrated into the signal or train control system be integrated into the PTC system. Thus, there would be a WIU at each signal already so that the signal indication could be enforced (Figure A6a). In this case, the on-board computer would have to enforce the restricted speed until a more favorable signal is reached. In the case of the ACSES system equipped with ATC, the restricted speed would be enforced until the train was beyond the point where the defect occurred (Figure A6b).



(a) I-ETMS (no modifications needed)

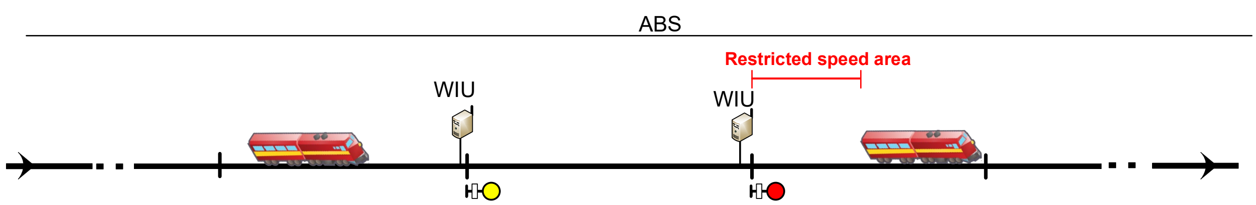


(b) ACSES (no modifications needed)

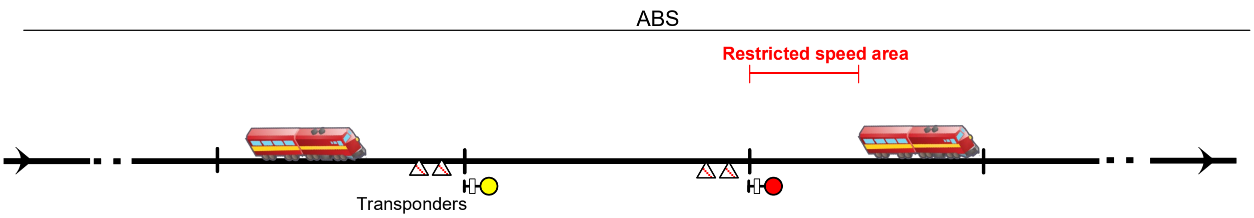
Figure A6. Scenarios in ABS with Alarmed Defect Detector in a) I-ETMS; b) ACSES

ABS – Occupied Block Ahead

In Figure A7, where there is a train in the block ahead, the signal system will react in the same manner as above (Figure A6). Most railroads allow a train to pass an ABS signal displaying STOP with the restricted speed. The second train could collide with the first train at the restricted speed. One of the alternatives to prevent this is to avoid restricted speed operations in the occupied block. A positive stop could be enforced at each ABS stop signal and permission would have to be received from the dispatcher to continue. This may prevent many rear-end collisions. To provide a positive prevention of a rear-end collision, an end of train device would be necessary to determine the location of the rear of the first train. The PTC system would have to have the capability to safely stop the second train before the collision with the first train. This would be a major upgrade to the PTC system.



(a) I-ETMS (no modifications needed)

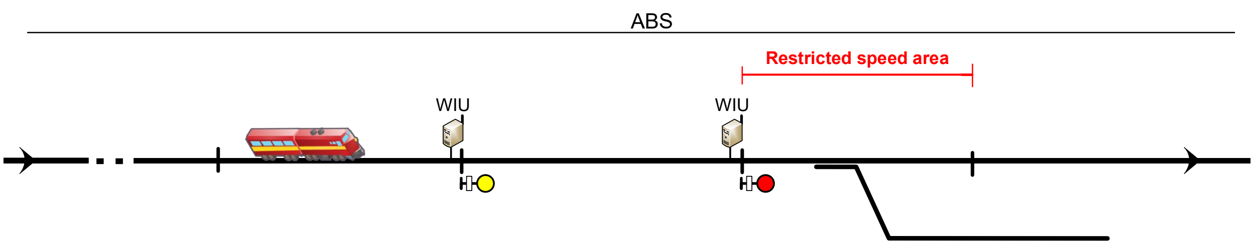


(b) ACSES (no modifications needed)

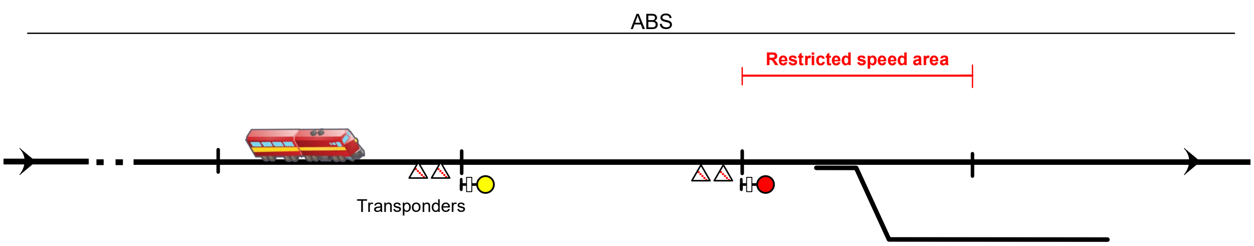
Figure A7. Restricted-Speed Scenarios in ABS with Occupied Block Ahead in a) I-ETMS; b) ACSES

ABS – Switch Improperly Lined

In the last sub-case in ABS (Figure A8), an open hand-operated switch in the block would cause the signal governing entry into the block to display STOP. The PTC system would enforce restricted speed, but the engineer may not be paying attention or may not be able to determine the position of the switch. A WIU would already be placed at the signal location to provide information to the train (Figure A8b). With the switch open or in an undetermined position, the PTC system could enforce STOP before the train passes the signal. Thus, no additional equipment is needed in either I-ETMS or ACSES to enforce restricted speed.



(a) I-ETMS (no modifications needed)

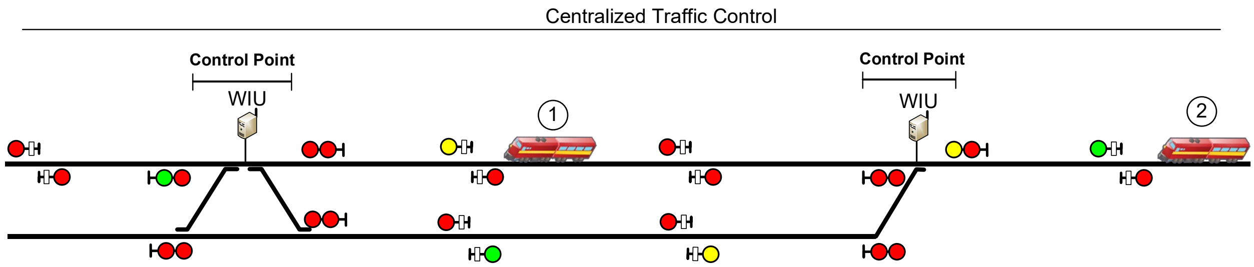


(b) ACSES (no modifications needed)

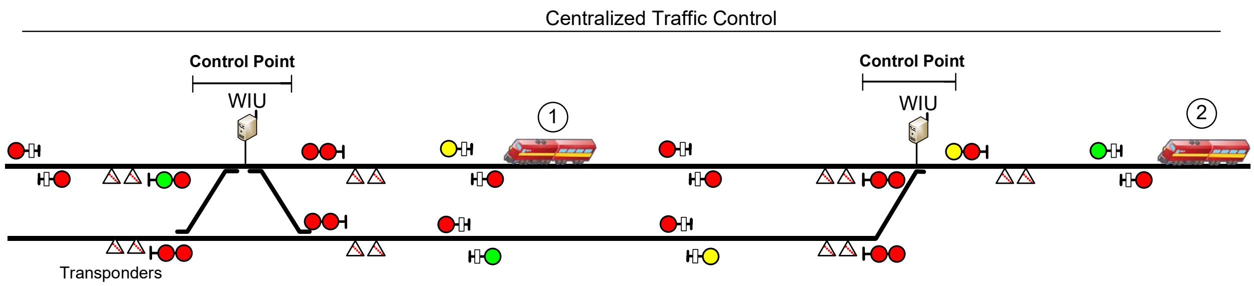
Figure A8. Restricted-Speed Scenarios in ABS with Improperly Switch a) I-ETMS; b) ACSES

Centralized Traffic Control

Centralized Traffic Control (CTC) consists of interlocking and automatic blocks, thus aforementioned restricted speed scenarios and proposed modifications in Figure A6 and Figure A7 are also feasible in CTC. In CTC territory (Figure A9), the PTC system will enforce absolute stop signals at the control points (refer to interlockings) or blocks. Most freight railroads allow trains to pass signals displaying Stop and proceed at the restricted speed. Most passenger railroads require a stop first and then the train may proceed at restricted speed. Others (especially freight railroads) allow trains to proceed at restricted speed without first bringing the train to a stop. This is commonly done where heavy freight trains are operating on upgrades where it may be hard to re-start the train after coming to a full stop. An ACSES system with ATC would enforce restricted speed in the cab.



(a) I-ETMS (no modifications needed)



(b) ACSES (no modifications needed)

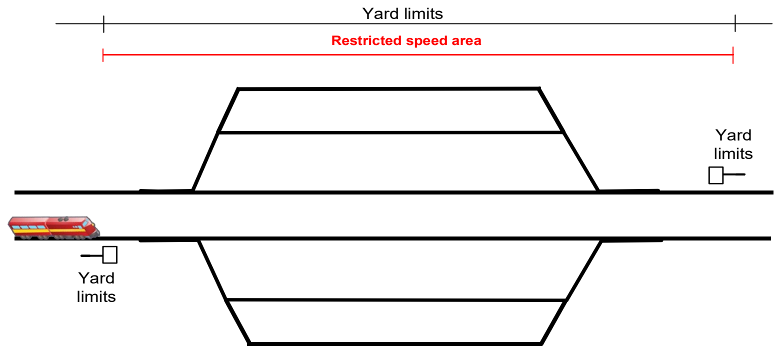
Figure A9. Restricted-Speed Scenarios in CTC a) I-ETMS; b) ACSES

Yard Limits

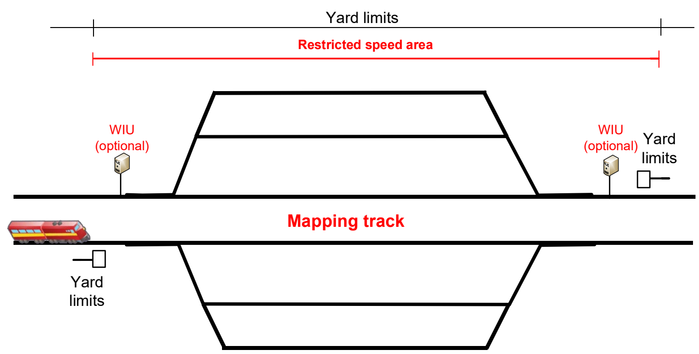
In Figure A10, a train is moving from PTC territory to yard limits which is defined by the yard limit signs at each end of the yard. When the train enters the yard limit area, the PTC system will disengage and will not enforce any speeds. By operating rule, most railroads require trains to move at restricted speed within yard limits.

To achieve the enforcement of restricted speed in I-ETMS system, the tracks must be mapped and designated as restricted speed tracks in the track database. With the tracks mapped, the I-ETMS system will remain engaged and will enforce restricted speed until the train leaves yard limits. Meanwhile, all the yard tracks do not have to be mapped. For example, the two main tracks in Figure A10 could be mapped and since the adjacent tracks are less than 50 feet from the main tracks the GPS system cannot distinguish that the train might not be on the main track. In that case, the system would continue to enforce restricted speed of both main tracks and yard tracks within yard limits, once if main tracks are mapped. If the railroad only wanted to enforce restricted speed on the main tracks, then a WIU would have to be installed at each end of the yard to monitor the switch leaving the main track. The I-ETMS system would disengage when the train left the main track.

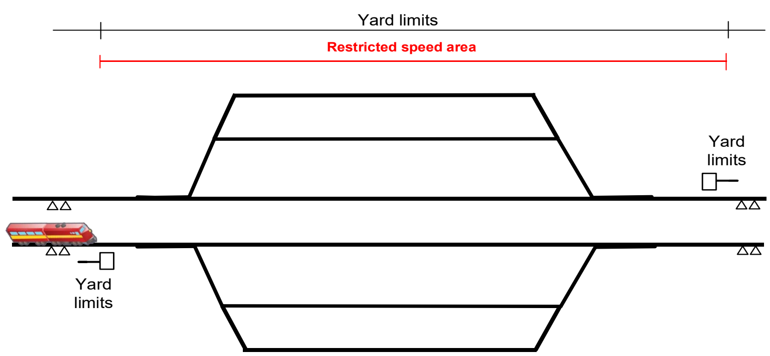
Since ACSES is used mostly by passenger railroads, this situation would be rare. However, even if it occurs, the ATC system would enforce restricted speed through the yard limit area and no WIU would be required.



(a) Without modifications in I-ETMS



(b) With modifications in I-ETMS



(c) ACSES (no modifications needed)

Figure A10. Restricted-Speed Scenarios in Yard Limits a) Without modifications in I-ETMS; b) With modifications in I-ETMS; c) in ACSES

Appendix B. Safe Benefit Calculation Spreadsheet

Table B1. Safety Benefits for PTC Preventable Accidents from 2001 to 2017

Cost Category	2001	2002	2003	2004	2005	2006	2007	2008	2009	2010	2011	2012	2013	2014	2015	2016	2017	Total
Fatalities	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$6,000,000**	**$0**	**$6,000,000**
Injuries	**$0**	**$0**	**$0**	**$366,667**	**$0**	**$0**	**$122,222**	**$0**	**$444,444**	**$0**	**$4,922,222**	**$444,444**	**$0**	**$0**	**$222,222**	**$19,366,667**	**$14,288,889**	**$39,244,444**
Employee Injuries	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$444,444*	*$0*	*$888,889*	*$444,444*	*$0*	*$0*	*$222,222*	*$666,667*	*$1,333,333*	*$3,555,556*
Passenger Injuries	*$0*	*$0*	*$0*	*$366,667*	*$0*	*$0*	*$122,222*	*$0*	*$0*	*$0*	*$4,033,333*	*$0*	*$0*	*$0*	*$0*	*$16,866,667*	*$12,955,556*	*$33,855,556*
Other Injuries	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$1,833,333*	*$0*	*$1,833,333*
Equipment Damage	**$15,778**	**$80,000**	**$35,106**	**$50,000**	**$13,400**	**$0**	**$80,600**	**$12,500**	**$339,500**	**$40,500**	**$241,717**	**$51,000**	**$0**	**$15,888**	**$70,300**	**$7,713,104**	**$4,902,864**	**$12,994,873**
Track and Right of Way Damage	**$432**	**$0**	**$1,468**	**$0**	**$14,000**	**$0**	**$0**	**$1**	**$28,000**	**$1,500**	**$326,183**	**$3,334**	**$0**	**$9,656**	**$4,752**	**$12,000**	**$446,000**	**$801,925**
Damage off the Right of Way	**$4,817**	**$2,408**	**$4,817**	**$2,408**	**$4,817**	**$0**	**$2,408**	**$0**	**$7,225**	**$4,817**	**$9,634**	**$4,817**	**$0**	**$2,408**	**$4,817**	**$4,817**	**$2,408**	**$28,901**
Hazardous Materials Cleanup	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Evacuations	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$60,210**	**$0**	**$42,147**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$42,147**
Loss of Lading	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**
Wreck Clearing:	**$93,326**	**$0**	**$101,153**	**$97,239**	**$0**	**$0**	**$3,914**	**$0**	**$97,239**	**$0**	**$190,565**	**$3,011**	**$0**	**$0**	**$93,326**	**$93,326**	**$279,977**	**$660,203**
Mobilize Equip	*$3,011*	*$0*	*$9,032*	*$6,021*	*$0*	*$0*	*$3,011*	*$0*	*$6,021*	*$0*	*$9,032*	*$3,011*	*$0*	*$0*	*$3,011*	*$3,011*	*$9,032*	*$27,095*
freight locomotive derailed	*$0*	*$0*	*$1,806*	*$903*	*$0*	*$0*	*$903*	*$0*	*$903*	*$0*	*$903*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$903*
freight car derailed	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
passenger train derailed	*$90,315*	*$0*	*$90,315*	*$90,315*	*$0*	*$0*	*$0*	*$0*	*$90,315*	*$0*	*$180,630*	*$0*	*$0*	*$0*	*$90,315*	*$90,315*	*$270,945*	*$632,205*
Delays	**$5,952**	**$0**	**$17,857**	**$11,905**	**$0**	**$0**	**$5,952**	**$0**	**$11,905**	**$0**	**$17,857**	**$5,952**	**$0**	**$0**	**$5,952**	**$5,952**	**$17,857**	**$53,572**
Freight Trains	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*	*$0*
Passenger Trains	*$5,952*	*$0*	*$17,857*	*$11,905*	*$0*	*$0*	*$5,952*	*$0*	*$11,905*	*$0*	*$17,857*	*$5,952*	*$0*	*$0*	*$5,952*	*$5,952*	*$17,857*	*$53,572*
Total in 2009 dollar	**$120,305**	**$82,408**	**$160,401**	**$528,219**	**$32,217**	**$0**	**$215,097**	**$12,501**	**$988,524**	**$46,817**	**$5,750,325**	**$512,558**	**$0**	**$27,952**	**$401,369**	**$33,195,865**	**$19,937,995**	**$62,012,553**
Total with reduction factor in 2017 dollar	**$102,473**	**$70,194**	**$136,626**	**$449,927**	**$27,442**	**$0**	**$183,215**	**$10,648**	**$842,006**	**$39,878**	**$4,898,017**	**$436,587**	**$0**	**$23,809**	**$341,878**	**$28,275,607**	**$16,982,805**	**$52,821,114**

Abbreviations and Acronyms

ACRONYM	DEFINITION
AAR	Association of American Railroads
ACSES	Advanced Civil Speed Enforcement System
ATC	Automatic Train Control
BCA	Benefit-Cost Analysis
BOS	Back Office Server
CBTC	Communications-Based Train Control
CFR	Code of Federal Regulations
CTC	Centralized Traffic Control
E-ATC	Enhanced Automatic Train Control
FRA	Federal Railroad Administration
GDP	Gross Domestic Product
GPS	Global Positioning System
I-ETMS	Interoperable Electronic Train Management System
ITCS	Incremental Train Control System
LIRR	Long Island Rail Road
NJT	New Jersey Transit
NTSB	National Transportation Safety Board
NPV	Net Present Value
OBC	Onboard Computer
OSA	Obstructive Sleep Apnea
PATH	Port Authority Trans-Hudson
PTC	Positive Train Control
PTS	Positive Train Stop
STAMP	Systems-Theoretic Accident Modeling and Processes
WIU	Wayside Interface Unit