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Prevention of End-of-Track Collisions at Passenger Terminals via Positive Train Control

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Abstract

A series of end-of-track collisions occurred in passenger terminals because of noncompliant actions from disengaged or inattentive engineers, resulting in significant property damage and casualties. Compared with other types of accidents, end-of-track collision has received much less attention in the prior research. To narrow this knowledge gap, this paper firstly analyzes the safety statistics of end-of-track collisions, then develops a fault tree analysis to understand the causes and contributing factors of end-of-track collisions. With the objective of mitigating this type of risk, this paper discusses the potential implementation of Positive Train Control (PTC) for the passenger terminal. This paper primarily focuses on the enforcement of the two most widely implemented systems, the Advanced Civil Speed Enforcement System (ACSES) and the Interoperable Electronic Train Management System (I-ETMS). For each implementation scenario, the Concept of Operations (ConOps) is proposed that depicts high-level system characteristics for the proposed PTC system enforcement at stub-end terminals. Ongoing work is being carried out by the authors to fully evaluate the cost-effectiveness and operational impacts of enforcing PTC in terminating tracks to prevent end-of-track collisions.

In the United States (U.S.), there are over 35 passenger terminals with multiple terminating tracks ending at bumping posts, platforms, or both (*1*). At these passenger terminals, the engineers' behavior plays a key role in safely stopping the train before reaching the end of the track. However, human errors and noncompliant behaviors (e.g., disengaged, incapacitated, or inattentive) may result in accidents.

In the past decade, there has been a series of end-of-track collisions in passenger terminals. For example, the New Jersey Transit (NJT) train accident at Hoboken Terminal (Figure 1*a*), New Jersey, on September 29, 2016, led to one fatality, 156 injuries, and around $6 million in damage costs. A similar end-of-track collision occurred at the Long Island Rail Road (LIRR) at the Atlantic Terminal (Figure 1*b*), New York, on January 4, 2017. It injured 112 passengers and crewmembers and total damage costs were estimated at $5.3 million (*2*). The engineers in both accidents failed to stop trains before they reached the end of tracks at passenger terminals.

The National Transportation Safety Board (NTSB) (*1*) stated that the safety issues identified from these two accidents also exist throughout the U.S. at many intercity passenger and commuter train terminals. To the authors' knowledge, the prior research focusing on end-of-track collision risk management is limited. This knowledge gap has motivated the development of this paper, which is part of an ongoing project to study passenger terminal safety and end-of-track collision prevention strategies.

The primary research objective of this paper is to analyze the potential implementation of Positive Train Control (PTC) to prevent end-of-track collisions at passenger terminals, with a focus on Concept of Operations (ConOps). Specifically, this paper aims to address the following questions:

1) What are the safety statistics of historical end-of-track collisions in recent years in the U.S.?
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?

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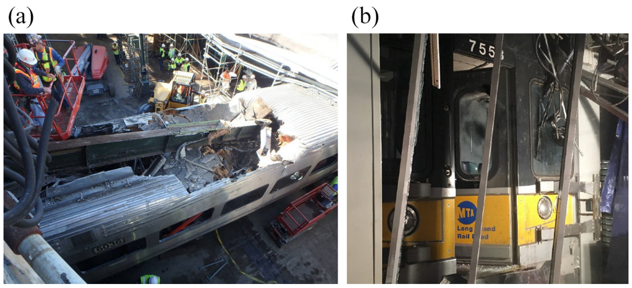


Figure 1. The train accidents of (*a*) NJT at Hoboken Terminal and (*b*) LIRR at Atlantic Terminal (*1*).

The answers to these questions would offer an understanding of 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. The research described in this paper is part of an ongoing research project. The operational impact assessment and cost-benefit analysis that would come with proposed PTC enforcement at terminals are beyond the scope of this paper, but will be presented in future papers.

Research Scope and Caveats

Because of the complexity of this subject and the content limit of this paper, it focuses on PTC enforcement to prevent end-of-track collisions because of human errors, instead of discussing all potential issues (e.g., train-to-train collisions, mechanical brake failures, broken rails). Some of these critical issues are being analyzed in the authors' ongoing work and will be presented in future studies. The following caveats should be born in mind when using this paper:

a) This research only focuses on PTC enforcement on terminating tracks. It is NOT the intention to propose PTC everywhere within a passenger terminal because of the close proximity of signals and switches, as well as the complexity of the track work.
b) The cost-benefit analysis and operational impact associated with proposed PTC enforcement in passenger terminals are beyond the scope of this paper, but will be presented in the authors' future papers.
c) Field testing should be conducted to verify and validate the ConOps proposed in this paper. This work is planned for 2019. Therefore, the currently proposed ConOps may be subject to refinement after the results from the field testing have been obtained.
d) This paper focuses on the passenger railroads and intercity or commuter passenger railroads which are regulated by Federal Railroad Administration (FRA). The PTC or PTC-alike technology implementations at transit terminals (e.g., light rail, subway) may be studied in the future research.
e) 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 the future research to promote the safety level of passenger terminals.

Literature Review and Intended Contributions

Extensive research has concentrated on train safety analysis related to train derailments, train collisions, and highway-rail grade crossing accidents (*3–7*). Although various types of train accident have received attention in the literature, end-of-track collisions at passenger terminals have rarely been studied. According to the statistics from the NTSB report (*1*), there are more than 35 passenger terminals with multiple tracks that end at bumping posts, platforms, or both, in the U.S. 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, or 15 miles per hour (*8–10*). 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) (*11, 12*). 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 (*1*). Bumping posts are safety devices placed at the end of terminating tracks to provide limited protection for low impacts. Previous studies (*1, 13*) stated that bumping posts did not provide adequate protection at passenger terminals and may fail at speeds over 10 mph.

There have been a number of end-of-track collisions at passenger terminals in the past decade. For example, LIRR trains experienced 15 collisions with bumping posts at passenger terminals in New York between 1996

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

Date	Location[b]	Railroad[c]	Speed (mph)	Injury	Fatality	Damage cost
Jan 4, 2017	Atlantic Terminal, NY	LIRR	12	112	0	$5,348,864
Sept 29, 2016	Hoboken Terminal, NJ	NJT	21	156	1	$6,012,000
Mar 7, 2016	Port Washington Station, NY	LIRR	2	0	0	$1,713,104
Jun 2, 2015	Hoboken Terminal, NJ	NJT	3	1	0	$23,802
Jan 6, 2014	LaSalle Street Station, IL	NIRC	7	0	0	$25,554
Sept 23, 2012	Jamaica Station, NY	LIRR	2	2	0	$12,000
Feb 21, 2012	Port Washington Station, NY	LIRR	3	0	0	$42,334
Jun 8, 2011	Princeton Station, NY	NJT	16	1	0	$53,500
May 8, 2011	Hoboken Terminal, NJ	PATH	13	35	0	$352,617
Mar 21, 2011	Port Jefferson Station, NY	LIRR	12	2	0	$110,283
Jan 27, 2011	New Canaan Station, CT	MNCW	7	0	0	$51,500

[a]Data sources: FRA REA database and NTSB railroad accident reports.
[b]Location: CT = Connecticut; IL = Illinois; NJ = New Jersey; NY = New York.
[c]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.

and 2010, and NJT also reported seven end-of-track collisions in the last ten years (*1*). In the last two years, the NJT train collision at Hoboken Terminal and the LIRR train collision at Atlantic Terminal each led to above 100 casualties and millions of dollars in damage costs, raising concerns from the public and rail industry. Overall, end-of-track collisions at terminals can lead to severe hazards for the onboard passengers, train crews, and bystanders, and can cause high-impact damage to rolling stock, wayside equipment, and terminal infrastructure.

In spite of the potential risk and the increasing concerns, to the authors' knowledge, limited prior research has been conducted on end-of-track collisions at terminals in the U.S. To narrow the knowledge gap, this paper conducts an analysis of end-of-track collisions and presents an end-of-track collision prevention strategy through the proposed PTC enforcement. In a special investigation report covering both the NJT accident at Hoboken Terminal and the LIRR accident at Atlantic Terminal, the NTSB pointed out one safety recommendation that "requires intercity passenger and commuter railroads to implement technology to stop a train before reaching the end of tracks" *(R-18-001) (1)*. Additionally, Moturu and Utterback stated that PTC can be one mitigation technique against end-of-track collisions (*13*). However, these studies contain conceptual oversights and there is a lack of detailed studies in specific modifications (e.g., what is needed and how to implement it) if the PTC system was enforced at passenger terminals. This paper offers a ConOps for the possible PTC enforcement at stub-end passenger terminals.

End-of-Track Collision Safety Analysis

Table 1 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 two data sources, the Rail Equipment Accident (REA) database of the U.S. FRA (*2*) and railroad accident reports by the NTSB. In relation to the FRA 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) and the FRA compiles these accident reports into the REA database. In addition to the basic accident information listed in Table 1, more comprehensive information can be found in the FRA REA database, including operational factors, environmental factors, train characteristics, damage costs, and narratives. Additionally, NTSB railroad accident reports describe the major findings of NTSB investigations including 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 particular public interest are involved in the NTSB investigations and then compiled into NTSB accident reports (*14*).

As shown in Table 1, from 2011 to 2017, data from eleven end-of-track collisions have been collected from the FRA REA database and NTSB investigation reports. In the U.S., over 35 passenger terminals have multiple terminating tracks ending at bumping posts, platforms, or both, and each of them has a large number of train stops every day (*1*). For example, the Chicago Union Station provides ridership for Amtrak and Metra. Per the publicly accessible train schedules, 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. Possible end-of-track collisions may bring hazards to the onboard passengers, train crews, and bystanders, and cause high-impact

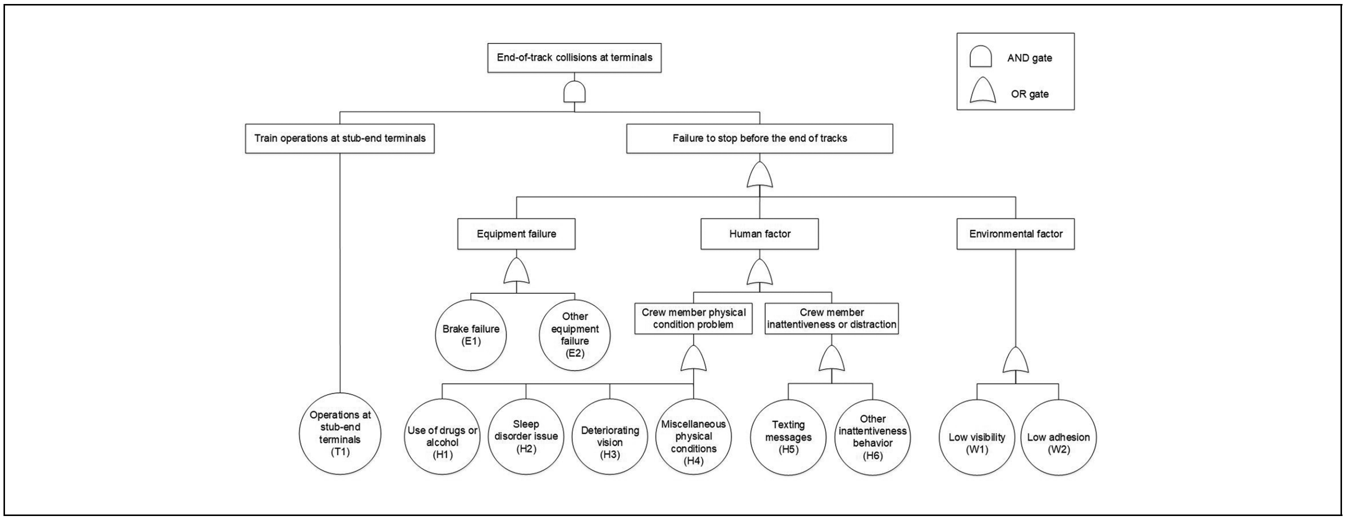


Figure 2. Fault tree analysis for end-of-track collisions at terminals.

damage to rolling stock, wayside equipment, and terminal infrastructure. Specifically, the selected eleven end-of-track collisions occurring between 2011 and 2017 have led to 310 casualties (injuries and fatalities) and over $13,745,548 total in damage costs. In relation to 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 two years and each led to over 100 casualties and over $5 million in damage costs to rolling stock and infrastructure. Both end-of-track collisions were caused by operational violations by the engineers, who both had Obstructive Sleep Apnea (OSA) (*1*). NTSB determined that the almost identical probable cause of two accidents was the failure of the train operators to stop the trains after entering terminals because of their fatigue resulting from severe OSA (*1*). Furthermore, NSTB 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. (*1*).

Fault Tree Analysis of End-of-Track Collisions

Fault tree analysis 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, identify safety-critical components, and eventually identify risk mitigation strategies. Since being conceived by H. A. Watson of Bell Telephone Laboratories, fault tree analysis has been used in various railroad safety studies, such as adjacent track accidents on shared-use rail corridors, train derailments, restricted-speed accidents, and high-speed railway accidents (*15–19*). 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.

Taking the NJT accident at Hoboken Terminal in 2016 as an example, the NTSB investigation report showed that the engineer's OSA led to his fatigue and ultimately to the occurrence of train operation failure (*1*). Thus, two basic events, operations at the stud-end terminal and the crewmember's sleep disorder, are connected with an AND gate in the fault tree. The simultaneous occurrence of two basic events would contribute to the occurrence of the NJT train collision at Hoboken Terminal.

Based upon historical accidents and engineering experience, a more comprehensive fault tree analysis of end-of-track collisions is in Figure 2. 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, namely equipment failures, human factors, and environmental factors. Brake failure is one case of equipment failure and can cause the failure of a train to stop before reaching the end of tracks. Low visibility because of adverse weather conditions (e.g., dense fog, snow) and low adhesion because of vegetation or extreme environmental conditions (e.g., ice) are among environmental factors that affect the 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 relation to human errors, crewmembers' physical condition problems (e.g., use of alcohol, sleep

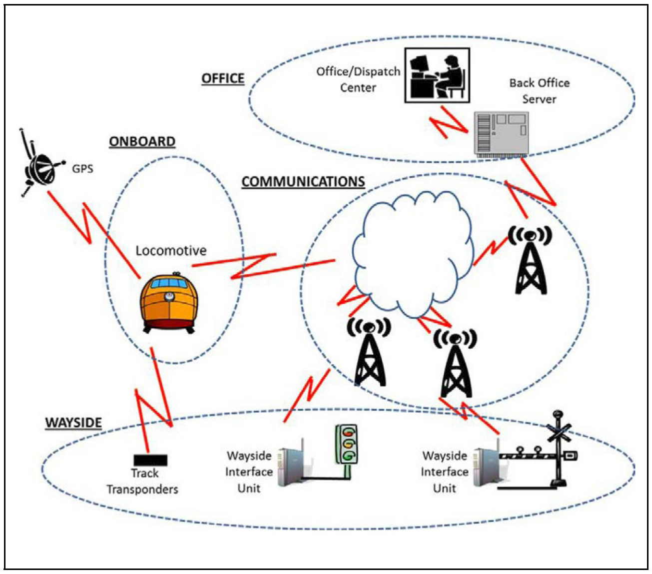


Figure 3. PTC systems architecture (*23*).

deprivation, deteriorating vision) and inattentive behaviors (e.g., texting) are likely to result in the violation of operating rules and may cause accidents.

Amongst the selected end-of-track collisions from 2011 to 2017 (Table 1), 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 FRA REA database, a sleep disorder issue (H2) is 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. This paper focuses on PTC as a potential solution. Other alternative strategies could be studied in future research.

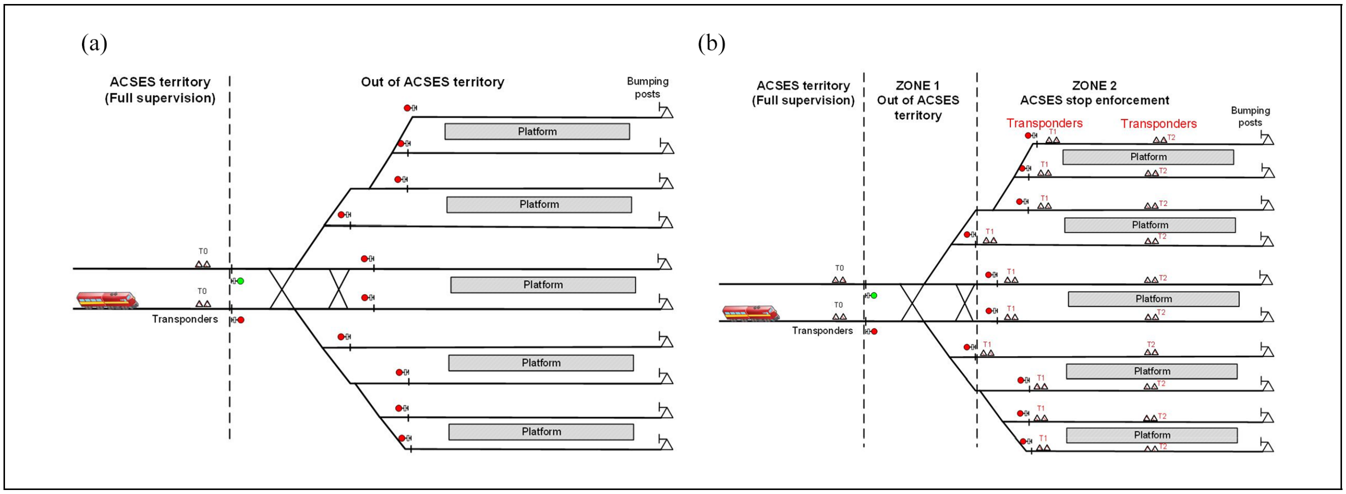
ConOps for PTC Enforcement on Terminating Tracks

Overview of the PTC System

PTC is a communication-based/processor-based train control system that is capable of reliably and functionally preventing train accidents attributable to human errors (*20*). To fully realize these functions, a PTC system integrates four main components (Figure 3), including the locomotive onboard computer, wayside device, communications network, and back office (*21*). The Advanced Civil Speed Enforcement System (ACSES) and Interoperable Electronic Train Management System (I-ETMS) are the two most common types of PTC system in the U.S. The ACSES-type PTC system is extensively utilized by the National Railroad Passenger Corporation (Amtrak) and most commuter railroads on the Northeast Corridor. The ACSES and Automatic Train Control (ATC) system work together to provide an FRA-approved PTC implementation. This system utilizes fixed transponders placed along the right-of-way to transmit "packages" of information (e.g., maximum authorized speed) to the passing trains, and then ACSES can enforce the speed restrictions and even a positive stop if risky human operations take place. I-ETMS is a Global Positioning System (GPS)-based system and is primarily implemented by Class I freight railroads. It uses the GPS system to determine the train's position in real time and contributes to the locomotive system safely enforcing a stop before the occurrence of human-error-caused train accidents. Note that the types of PTC systems approved by the FRA are not limited to these two. For example, the Incremental Train Control System (ITCS) is used by Amtrak on the Michigan Corridor, Enhanced Automatic Train Control (E-ATC) is implemented by Portland & Western Railroad (PNWR) and several passenger railroads, and Communications Based Train Control (CBTC) is currently deployed by Port Authority Trans-Hudson (PATH), which operates as an intraurban heavy rail transit system. Although PATH is not physically connected to the general freight and passenger rail network, it remains under the jurisdiction of FRA because of the fact that PATH was previously part of the general freight railroad (*22*).

According to 49 CFR 236 Subpart I, PTC is not required to perform its functions when the train is approaching terminals, because of restricted speed operations (*8*). Specifically, the terminating tracks were identified in a mainline track exclusion addendum (MTEA). MTEA is the document submitted under Title 49 Code of Federal Regulations §236.1019 Main Line Track Exceptions, requesting to designate tracks as non-mainline and for trains to move under restricted speeds (*8*). Without the implementation of the PTC system, stopping a train on a terminating track under MTEA would still depend on the attentiveness and compliant behavior of the engineer.

This paper proposes the potential use of the PTC system to automatically stop a train before the end of the tracks if the engineer is negligent or disengaged. To explore how PTC systems may function if the systems were enforced at passenger terminals, specific modifications are proposed and a "what-if" scenario-based analysis is performed. This paper primarily focuses on the enforcement of the two most widely implemented



Figures 4*a* and 4*b*. A simplified stub-end terminal: 4*a* without ACSES and 4*b* with ACSES enforcement.

systems, the ACSES system and the I-ETMS system, which account for the vast majority of PTC systems installed in the U.S. Discussions of other types of PTC systems will be studied in future research.

Concept of Operations with ACSES

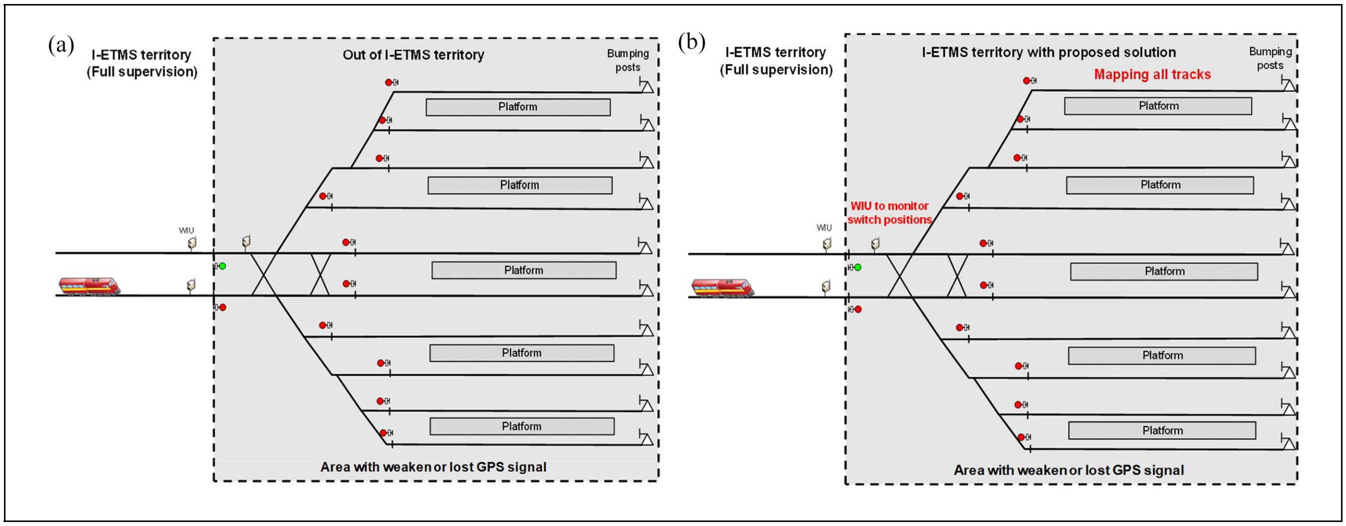
In the ACSES-type PTC system, a set of transponders (two transponders in one set) located right before MTEA (Figure 4*a*) mark the end of the full ACSES territory at the end of a main track. When the train reaches this point, this set of transponders would inform the onboard ACSES system that it is entering "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 (*9, 10*). The ATC system in U.S. railroads integrates with cab signals and involves speed enforcement. Specifically, 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.

The proposed solution is to divide the terminal area into two zones and to install additional transponder sets at the second zone, as shown in Figure 4*b*. The first transponder set (T1 in Figure 4*b*) causes the train system to re-enter ACSES territory and provides positive train stop (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 than or equal to the braking distance needed to stop the train safely. The second transponder set (T2 in Figure 4*b*) 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 4*b*).

Concept of Operations with I-ETMS

As mentioned previously, 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



Figures 5*a* and 5*b*. A simplified stub-end terminal: 5*a* without I-ETMS and 5*b* with I-ETMS enforcement.

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 5*b*). 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 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 permit it to travel before enforcing a positive stop. To achieve this, Wayside Interface Unit (WIU) would be required to be installed 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.

Ongoing Work

The proposed ConOps provides potential options for end-of-track collision prevention with PTC, particularly for ACSES- and I-ETMS-type PTC systems. Ongoing work is being conducted to study the cost-benefit analysis, operational impacts, and practical engineering challenges associated with PTC enforcement at stub-end terminals. This section only offers the high-level perspectives of this ongoing work. More thorough analytical results and conclusions will be presented in the future.

Cost-Benefit Analysis

In the cost-benefit analysis, the incremental cost associated with PTC enforcement at stub-end terminals mainly includes (but is not limited to) four components: (1) the hardware cost for newly added equipment, including the labor cost to install hardware and miscellaneous material costs; (2) the design cost from developing plans for the implementation and operation of the proposed PTC enforcement on terminating tracks within terminals; (3) the cost of training tests; and (4) the maintenance cost for all system components. The cost estimation methodology is drawn from an FRA report that provides the general cost calculation of nationwide PTC implementation (*23*). The unit cost information can be gathered from railroads and vendors. Based on the proposed ConOps above, the costs for ACSES-type terminals would mainly be for transponder installations. For I-ETMS-type terminals, the incremental costs would be for installing WIU(s) and mapping tracks. Therefore, the total incremental costs may not be significant because major PTC components (e.g., onboard devices) have been installed to achieve PTC functions in active territories. Besides incremental costs, the potential safety benefits (reduction of end-of-track collisions) of the proposed PTC implementation will also be considered, based on the historical accident records from the FRA REA database and NTSB investigation reports. To calculate the monetary value of safety benefit, previous studies considered equipment damage, track and right-of-way damage, hazardous materials cleanup, loss of lading, wreck clearing, train delay, and casualties (*22, 24*). Correspondingly, a cost-benefit analysis can be developed for a studied period (e.g., 20 years after PTC implementation on terminating tracks).

Operational Impact Assessment

The braking algorithms used in the PTC systems and the probable PTC component failures have been studied in previous research. In relation to braking algorithms, a safety factor is applied to account for the situations where rail adhesion is affected by rain, snow, ice, and other factors, built on the baseline braking algorithms derived from the tests on dry rail and a relatively level tangent track. In previous studies, Mokkapati and Pascoe developed a simple PTC braking algorithm for freight and passenger trains (*25*). A correction factor is used to account for the variations in multiple parameters and to ensure an acceptable probability of stopping at a targeted point if parameters are under "worst case" scenarios. For example, the correction factor of a passenger train with headend locomotives only is 1.11, which would be used to develop braking algorithm by multiplying it with the nominal braking distance. Pate et al. also investigated methods for enhancing PTC braking algorithms in freight trains considering track grade and evaluated them via the Monte Carlo simulations (*26*).

Regarding probable PTC component failure, Hartong et al. provided a taxonomy of PTC system failures and pointed out that PTC failure includes onboard system failure, communication failure, loss of power, and wayside system failure (*27*). In a study of I-ETMS risk assessment using the BNSF San Bernardino as a case study, Brod and Leslau accounted for PTC equipment reliability in the train operation simulation and classified PTC failures into two major types: failure to warn and failure to enforce braking (*28*). Integrating the information from prior studies, Monte Carlo simulation may be one possible methodology to use to conduct the operational impact analysis for the proposed PTC enforcement on terminating tracks.

Engineering Considerations

Additionally, 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. The studies of these engineering challenges, as well as the aforementioned cost-benefit analysis and operational impacts, are ongoing and will be presented in the future. 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, it might be worth developing in future research implementable 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.

Conclusion

Several end-of-track collisions occurred at passenger terminals, resulting in property damage and casualties. The fault tree analysis based upon past end-of-track collisions shows that human error is a primary accident cause. To reduce this risk, the potential PTC enforcement on terminating tracks is proposed to enforce safe train operation. A system-specific (I-ETMS and ACSES, respectively) ConOps is proposed, which provides information regarding what is needed to enforce PTC and how to implement it, to prevent end-of-track collisions because of human errors. Ongoing research is being undertaken by the authors to evaluate the cost-effectiveness of the proposed ConOps, as well as its operational impact.

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Author Contributions

The authors confirm contribution to the paper as follows—Study conception and design: ZZ, XL, KH; Data collection, analysis and interpretation of results: ZZ, XL, KH; Draft manuscript preparation: ZZ, XL, KH. All authors reviewed the results and approved the final version of the manuscript.

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