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Positive Train Control (PTC) for railway safety in the United States: Policy developments and critical issues

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ABSTRACT

Nationwide implementation of Positive Train Control (PTC) is underway in the United States. PTC is designed to prevent certain types of train accidents. This paper provides a review of the policy development, operational impact, cost-effectiveness, and critical issues associated with industry-wide PTC implementation. Challenges include interoperability, technological complexity, and limited implementation resources. Emerging critical issues include train operations at restricted speeds, railroad cyber-security risk, broken rail prevention in PTC territories, en route failure of PTC, grade-crossing protection, and opportunities for leveraging PTC-generated big data that require more research from academia, government, and industry.

1. Introduction

Rail transportation plays a vital role in the national economy of the United States. Safety is an obvious priority for rail transportation systems. In the United States, railroad safety has improved through the development and enforcement of safety regulations, along with research and development of advanced technologies over several decades. Although national train accident rates have declined by over 80 percent since 1980 (FRA, 1980, 2015a), accidents still occur annually due to various causes. For example, 25 severe accidents (15 freight accidents and 10 passenger accidents) occurring between 2001 and 2008 were caused by human error (FRA, 2016a).

Train accidents receive substantial media attention and raise the issue of safety and potential solutions, including Positive Train Control (PTC), on the national agenda. Some recent accidents include:

- Amtrak passenger train 501 derailed from a highway overpass near DuPont, Washington, on December 18, 2017, with 3 fatalities and 62 injuries (NTSB, 2018a).
- Amtrak passenger train 89 collided with maintenance-of-way equipment near Chester, Pennsylvania, on April 3, 2016, with 2 fatalities and 39 injuries (NTSB, 2017a).
- Two Union Pacific Railroad freight trains collided near Texarkana, Texas, on September 8, 2015, and led to 2 injuries, release of 4000 gallons of diesel fuel, as well as around $4.66 million damage cost (NTSB, 2017b).

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.

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 would involve around over 60,000 route miles (AAR, 2017; FRA, 2017b). 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).

As a federal mandate, PTC technology has been studied in federal regulations and industry reports (RSAC, 1999; FRA, 2009; Van Dyke and Case, 2010; Peters and Frittelli, 2012; GAO, 2015; AAR, 2017). The objective of this paper is to provide readers (especially non-PTC experts) with a full-spectrum introductory view of PTC technology, challenges related to the development and deployment, safety benefits,

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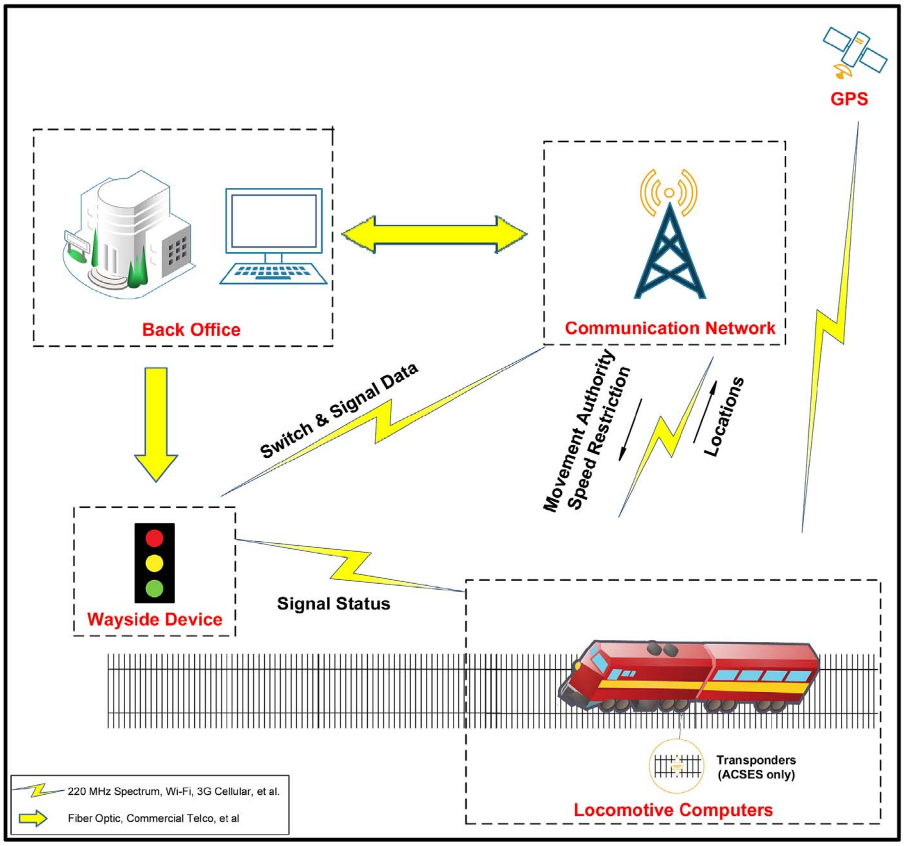

Fig. 1. Schematic illustration of a general PTC system.

and implementation impact and cost. The paper also discusses emerging critical issues in the age of PTC.

2. PTC technology

2.1. The basics of PTC

PTC systems must meet the functionality requirements established by the Rail Safety Improvement Act (RSIA) of 2008 in terms of capability to prevent accidents resulting from the activity or inactivity of train operators. PTC is not a single technology. Instead, it is a suite of performance standards. Railroads are allowed to install different PTC technologies in their respective systems once approved by the Federal Railroad Administration (FRA).

PTC integrates various components (Fig. 1), namely the locomotive computer, wayside device, communication network, and back office (APTA, 2015; AAR, 2017). The locomotive computer is an onboard piece of equipment that 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 office 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 (the back office server (BOS), the geographical information system (GIS), and the 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 communication 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, 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.

2.2. History and implementation

Rudimentary elements of PTC have existed since the early 20th century. Regulators and safety advocates have pushed the rail industry to implement PTC systems for decades (FRA, 2016a). In 1990, the National Transportation Safety Board (NTSB) included PTC as one of the most wanted safety technologies in the United States (NTSB, 1991; FRA, 2016a). Railroads subsequently developed and started to deploy train control systems on a small scale. For example, in the 1990s, Amtrak started to deploy the Advanced Civil Speed Enforcement System (ACSES) on its Northeast Corridor, and the Incremental Train Control System (ITCS) on approximately 60 route-miles between Chicago and

Detroit. At the end of the 1990s, CSX Transportation, Inc. (CSX) started to develop a PTC system that used GPS to identify train location (FRA, 2016a).

On September 12, 2008, a Metrolink commuter train collided with a Union Pacific Railroad train in the Chatsworth district of Los Angeles, California, causing 25 deaths and more than 100 injuries. The accident report from the National Transportation Safety Board (NTSB, 2010) showed that the train engineer was texting and failed to stop for a red signal. This accident was PTC-preventable. After the Metrolink accident, Congress passed the Rail Safety Improvement Act of 2008 (RSIA), which mandated the implementation of PTC before December 31, 2015 (Congress, 2008). The RSIA and relevant policies (CFR, 2011; FRA, 2010; 2014b, 2016c) specified the function of the PTC system, as well as the implementation territory.

Responsibility for implementation of PTC rests with the Federal Railroad Administration (FRA), which was established in 1966. It is an agency in the U.S. Department of Transportation that was created by the Department of Transportation Act of 1966 (Congress, 1966). The mission of the FRA is to facilitate the safe, reliable, and efficient movement of people and goods in the United States through promulgation and enforcement of safety regulations, promotion of rail infrastructure and services, data-driven analysis, and research and development of emerging technologies and innovative solutions in support of rail safety and operational performance (FRA, 2017d; USDOT, 2017). Enacted budget in the fiscal year 2017 is $1851 million (USDOT, 2017).

In October 2015, the Positive Train Control Enforcement and Implementation Act of 2015 (PTCEI Act) extended the deadline to December 31, 2018, given significant implementation challenges reported by the railroad industry (GAO, 2013; Congress, 2015b; FRA, 2016c). The PTCEI Act also required railroads to submit a plan that includes an explicit schedule and sequence for implementing PTC by the new deadline. The FRA can approve a railroad's alternative schedule and grant an additional extension up to December 31, 2020 only for the implementation of certain operational, non-hardware aspects of PTC systems (Congress, 2015b). Fig. 2 shows the PTC statutory timeline from 2008, the year that RSIA was enacted, to the conditional deadline in 2020.

To complete a nationwide interoperable PTC-system before the mandated deadline, U.S. railroads have invested in infrastructure, equipment, signaling, and training. In addition, the FRA monitors railroads' progress, including reviews of railroads' PTC implementation plans, annual reports on the status of railroads' PTC implementation, and quarterly reports and compliance reviews. Fixing America's Surface Transportation Act of 2015 (FAST Act) (Congress, 2015a) also authorized grants for supporting PTC implementation in the United States.

The overall implementation progress is summarized in Table 1, which is based on data through September 2017. It indicates that most PTC components are less than 75% complete with around one year until December 31, 2018. Major reasons behind this are the significant challenges in developing and deploying PTC, as clarified in the next section.

2.3. *Significant implementation challenges*

Although considerable progress is being made toward the completion of a nationwide interoperable PTC network, railroads are encountering a number of significant implementation challenges associated with interoperability, technical complexity, and resource constraints.

2.3.1. *Interoperability*

Interoperability, as defined by RSIA, means that PTC must be able to communicate with one another so trains can seamlessly move across track owned by different railroads with potentially varying PTC technologies (GAO, 2015). It means that the railroads (as “hosts”) should ensure their PTC systems are interoperable with trains from other railroads (as “tenants”) that might run on the host's track. More specifically, the tenants should constantly communicate with hosts' back office and also contact with all WIUs on their route, regardless of their affiliation with a particular railroad.

Interoperability is essential and significant given that there are up to 43 freight, intercity passenger, and commuter railroads that are required to implement PTC (FRA, 2017a), and U.S. railroads frequently use one another's track with access contracts. Interoperability among these railroads is a significant challenge in the development and deployment of PTC systems, requiring both hardware and software upgrades. As railroads continue implementing PTC systems on their own tracks and relevant equipment, the interoperability among the railroads' PTC systems will remain a major issue. Most track segments where PTC will be implemented throughout the U.S. have not reached a mature stage of interoperability (FRA, 2016a).

There are several challenges regarding the implementation of nationwide interoperable PTC systems. First, a fully interoperable PTC system amongst different railroads requires substantial upgrades to key elements in railroad operations (locomotive computer, wayside device, communication network, and back-office server). Young (2016) pointed out that the complexity and scope of these upgrades could introduce substantial technical issues that must be identified and corrected through extensive testing. Second, development of industry interoperability standards is challenging and potentially expensive. The scope, complexity, and difficulty of PTC interoperability exceeded what was originally anticipated (FRA, 2012). Without detailed interoperability standards and specifications, preparation of contract documents to develop and implement PTC has been delayed (FRA, 2012). In addition, Lee and Mahony (2017) argued that PTC vendors might seek to protect their intellectual property and confidential information in order to maximize their competitive advantage. Although such vendor efforts are understandable, they may affect disclosures by railroads regarding PTC interoperability.

2.3.2. *Technical complexity*

PTC systems are comprised of several highly complex technologies that are capable of receiving, analyzing, and incorporating numerous variables to facilitate train operations. Prior research has identified some of the technological challenges of PTC, in particular, determination of braking distance and establishment of communication networks

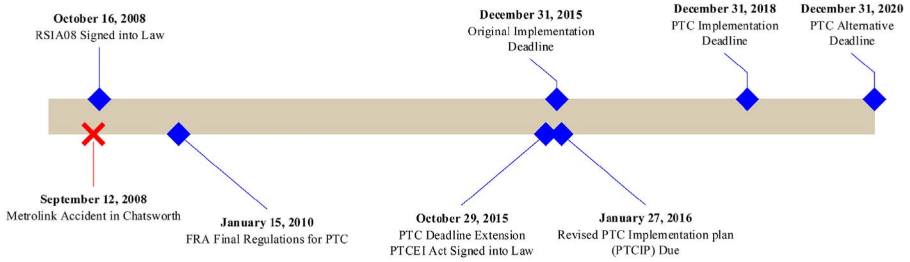

Fig. 2. PTC statutory timeline, from 2008 to 2020 (created based on FRA, 2016b).

Table 1
PTC implementation status, up to September 2017 (FRA, 2017b).

	Freight train			Passenger train		
	Total	Completed	Percentage	Total	Completed	Percentage
Route miles	54,185	24,535	45%	4147	1008	24%
Locomotives	17,432	11,804	68%	3935	1967	50%
Track segments	634	377	59%	208	51	25%
Training	103,093	84,141	82%	25,707	17,039	66%
Radio towers	16,508	14,988	91%	1235	790	64%

(Pascoe and Eichorn, 2009; Dingler et al., 2010; Moore Ede et al., 2009; AAR, 2014; FRA, 2016a).

The distance necessary to stop a running freight train depends on train speed, terrain, train length, car and freight weight, braking efficiency, the number and distribution of locomotives, loaded and empty freight cars on the train, adhesion, and other factors (Dingler et al., 2010; AAR, 2014). An onboard computer must be capable of taking all these factors into consideration in order to alert the operator or stop the train automatically if the locomotive violates a speed restriction or movement authority. These factors may not be accurately known when a train leaves the terminal, resulting in uncertainty regarding the exact braking distance required (Anderson, 1995; Moore Ede et al., 2009). Studies conducted by Thurston (2004) and Dingler et al. (2010) show that there are differences between the estimated braking distance and actual braking distance, even when many of these factors are known.

The other key challenge is deploying a 220 MHz communications network for a national and interoperable PTC system. As a key component of PTC, a commonly used communications network using a spectrum in the 220 MHz band should provide sufficient coverage to operate PTC and avoid interference, so that data can be reliably transmitted and received. This could be particularly challenging in congested metropolitan areas where multiple railroads are running different PTC systems, as they will have to address potential interference. Some new PTC users may even have to re-engineer their radio networks to comply with PTC being used or tested by other railroads. (AAR, 2014; GAO, 2015). In 2016, the FRA published a technical report, in which a PTC desense mitigation test was conducted in the Northeast Corridor (NEC) PTC deployment (Nast et al., 2016). Adaptive interference canceller (AIC) technology and radio frequency (RF) filters were identified as two PTC radio desense mitigation recommendations. Although various tools are being developed to help mitigate communications interference, this will remain an important task requiring further analysis and implementation.

2.3.3. Resource constraints

Capital cost constraints remain an issue that prevents many freight and commuter railroads from meeting the PTC deadline. U.S. freight railroads are privately owned and have a limited budget for a variety of safety investment. Spending on PTC may delay or reduce spending on other safety programs (AAR, 2011). AAR (2011) asserted that the expenditures on PTC necessarily lead to reduced expenditures on other projects to increase capacity, promote service, and even improve safety in more effective ways. Van Dyke (2010) similarly suggested that Class I railroads may need to divert capital away from infrastructure-related spending because of PTC implementation. Commuter railroads are publicly funded and have limited resources for safety improvement (APTA, 2015). The American Public Transportation Association (APTA) estimated that commuter and passenger railroads will need to spend approximately $3.5 billion to implement PTC. Similarly, many shortline railroads lack funds to upgrade their locomotives that operate over Class I PTC territory (APTA, 2015; FRA, 2016a). In addition, limits in the supply chain will also affect the development and deployment of nationwide PTC systems. GAO (2013) pointed out that only a small number of vendors can design PTC systems and supply PTC hardware and software. As a result, the PTC component prices and implementation costs might increase with expanded demand.

Furthermore, as mentioned in Section 2.3.1, challenging interoperability issues persist amongst freight, intercity passenger, and commuter railroads. PTC system are required to be tested to ensure that PTC works in operation on other railroads' networks. However, the host railroads may not be able to complete PTC implementation by December 31, 2018, but the tenant railroad's equipment, such as locomotive computers, is ready for PTC operation. Anticipating this possibility, Amtrak has considered suspending train operations on such routes until the host railroad completes PTC implementation (Amtrak, 2018).

3. Safety impact and cost of PTC

3.1. Safety benefit

According to the U.S. Congressional Research Service, PTC was expected to prevent less than 2% of the approximately 2000 railroad collisions and derailments that occur annually (Peters and Frittelli, 2012). AAR (2011) estimated that only around 4% of all train accidents on Class I rail main lines are likely to be prevented by PTC. A report by the Railroad Safety Advisory Committee (RSAC) to the FRA (hereinafter the “1999 Report”), which was supported by the FRA, the Volpe National Transportation Systems Center (Volpe Center), and NTSB, found that PTC-preventable accidents (PPAs) may lead to high consequences, usually involving fatalities, injuries, or major equipment damage. Compared with non-PPAs, the 1999 Report and the FRA (2009, hereinafter the “2009 Report”) agreed that PPAs have lower probability but potentially higher consequences, particularly when involving hazardous materials or passengers.

In recent years, most literature (AAR, 2011; Peters and Frittelli, 2012; GAO, 2013) cited the estimation of safety benefits from the 2009 Report (FRA, 2009) by a joint working group. In that report, in order to estimate PTC safety benefits from 1988 to 2001, 728 PPAs were identified. These accidents were classified into two categories: baseline accidents and headline accidents. The reason behind this classification is to avoid underestimating certain high-profile accidents, which are very infrequent and unique in circumstance, but result in extensively severe consequences. To systematically evaluate safety benefits, costs were assigned to each PPA, using a cost assignment methodology, in which specific costs were assigned to each type of accident consequence, such as fatalities, injuries, evacuations, track and right-of-way damage, and loss of lading (Fig. 3). For example, the unit costs of fatalities, employee injuries, and passenger injuries were assigned as $6,000,000, $222,222, and $122,222, respectively, in 2009 dollar. Given a 20-year life cycle, the estimated safety benefits of PTC implementation are approximately $440 million (using a 7% discount rate) and $674 million (using a 3% discount rate).

3.2. Implementation cost

The cost of PTC implementation has raised concerns since RSIA came into effect. The FRA (2009) estimated PTC implementation costs

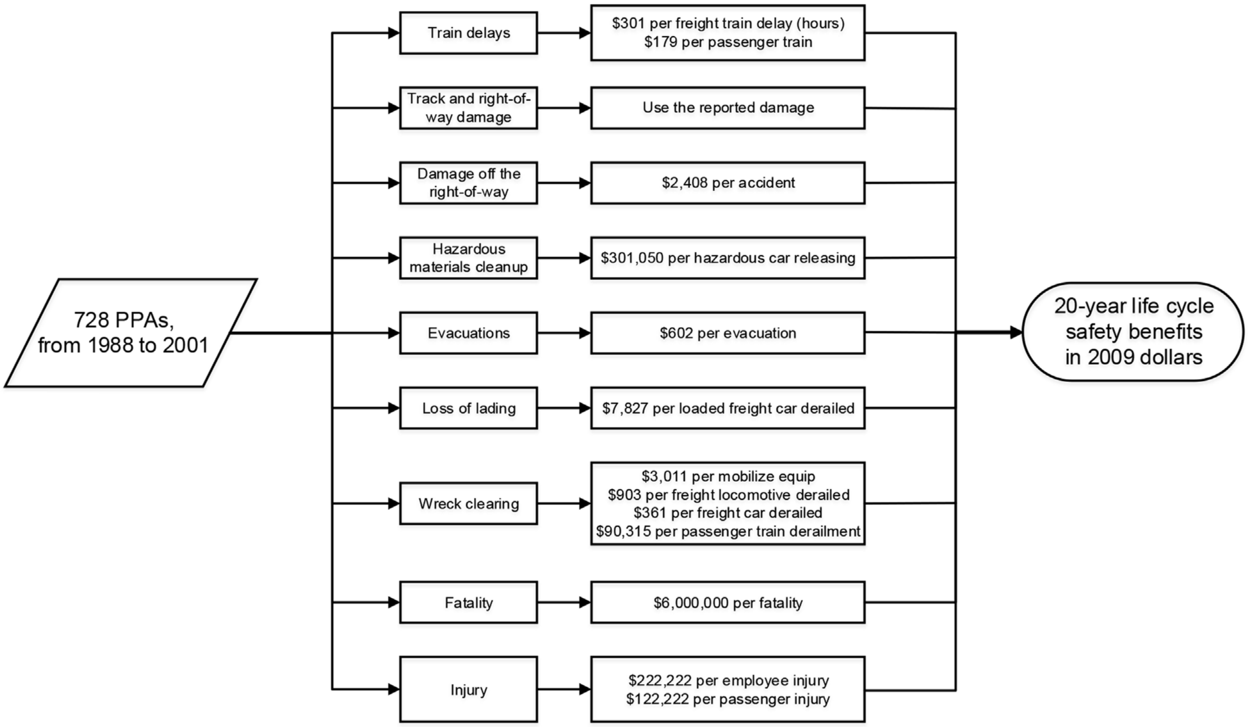

Fig. 3. Cost assignment for estimating PTC safety benefit (adapted from FRA, 2009).

in terms of locomotive installation costs, wayside installation costs, and maintenance costs for all system components. The FRA (2009) estimated the total 20-year cost at $9.55 billion (using a 7% discount rate) and $13.21 billion (using a 3% discount rate). Based on the safety benefits identified in the 2009 Report, this implies a 20-year cost-to-benefit ratio of 21.7 for nationwide PTC implementation. In other words, PTC will yield $1 in safety benefit for approximately every $20 spent on it (AAR, 2011), the implications of which have raised industry-wide concerns. For perspective, Peters and Frittelli (2012) stated that the annual fixed-capital investment by U.S. railroads in 2010 came to $11 billion, of which $7.8 billion was for infrastructure and $3.2 billion was for equipment. The estimated capital cost of meeting the PTC mandate is thus roughly equal to the railroads' total capital spending in a single year. AAR (2011) argued that a large amount of spending on PTC means less money will be available for other critical infrastructure and safety-enhancing projects.

These benefit and cost estimates are likely to be revisited for several reasons. First, all currently available reports use December 2015 as the original deadline, which has been extended to December 2018. A change in the PTC implementation deadline may influence estimates of both benefits and costs. The estimated safety benefit for any particular year must be calculated based on the percentage of PTC implementation completed. With a longer installation period, railroads will be able to avoid overtime work rates, thus lowering costs. Second, costs will change with the adoption of standards related interoperability and communications and next-generation technological advances. Third, the 1999 and 2009 Reports rely on data that are now more than a decade out of date. Over the past ten years, accident frequency and severity, as well as traffic exposure have changed. Liu (2015) found that the freight train derailment rate per million train-miles in 2012 was 0.52, which is only half the rate in 2000 and had declined by 5.8% annually from 2000 to 2012. All else being equal, a reduced accident rate reduces the estimated value of benefits. Future analysis is needed to more accurately estimate both implementation costs and safety benefits and inform policy development and decision-making.

4. Operational impact of PTC

The FRA (2009) analyzed the operational impact of PTC in terms of precision dispatch, capacity enhancement, and fuel savings. Despite the potential for these operational and business co-benefits, once PTC systems have been refined, the 2009 FRA Report recognized uncertainty in this area. AAR (2011) and GAO (2013) argued that these impacts were already realized by other technologies or have little relevance to PTC. Van Dyke and Case (2010) found no direct relationship between some operational impact and PTC implementation. For example, precision dispatching may result in fuel savings as well as increased railcar velocity and line capacity. Norfolk Southern (NS) and Union Pacific (UP) argued that the benefits of precision dispatching are realized without the use of PTC. They have developed a precision dispatching system without using PTC and preliminary results indicate some benefits. In some cases, PTC might even make existing rail operations less efficient and reduce network capacity due to conservative braking algorithms. Van Dyke and Case (2010) stated that the European Railway Traffic Management System (ERTMS), a PTC-alike system currently used in Europe, had a negative effect on network capacity. However, both AAR and Oliver Wyman anticipated positive operational impact and business benefits from next-generation PTC systems, such as full computer-based train control (CBTC) (Petit, 2009; Peters and Frittelli, 2012) or PTC with a dynamic headway system on active communications (Zhao and Ioannou, 2015).

5. Emerging issues and research opportunities

This section identifies major critical issues and knowledge gaps in the age of PTC, including train operations under restricted speeds, railroad cyber security, detection and prevention of broken rails in PTC territories, en route PTC failure, grade-crossing safety improvements with intelligent trains and vehicles, and opportunities for leveraging PTC-generated big data. These issues introduce new challenges and research opportunities and can serve as an agenda for the railroad industry, regulators, and academics to enhance the rail safety with the implementation of PTC systems.

5.1. PTC under restricted speed

As defined by current regulations (49 CFR 236 Subpart G), restricted speed is a speed that will permit stopping within one-half the range of vision, but not exceeding 20 miles per hour. In the United States, restricted speed operation is a common type of train operation that is commonly found on virtually every mile of automatic blocks and also extensively exists in terminals and yards. NTSB issued a report in 2012, highlighting five rear-end collisions due to violating restricted speeds (NTSB, 2012). One of them led to two fatalities and more than $8 million damage cost. More recently, a Long Island Rail Road (LIRR) passenger train collided with the platform in the Atlantic Terminal in New York City on January 4, 2017. The accident, which occurred inside the terminal (where traveling under restricted speeds is required), led to 108 injuries and around $5.3 million damage cost (NTSB, 2018b).

Current regulations (49 CFR 236 Subpart I) do not require PTC to perform its functions when a train is traveling under restricted speeds. Transportation Economics & Management Systems Inc. (TEMS, 2017) argued that the defined 20-mph restricted speed might be too fast and could be reduced to 10-mph. There is little analysis yet showing the rationality of either the 20-mph or 10-mph restricted speed or the performance of PTC below restricted speeds. Research is needed to better understand the safety benefits, cost, and operational impact of PTC enforcement at or below restricted speeds. The railroad industry and its regulators could use this type of analysis to evaluate whether PTC implementation should be extended to restricted speeds (if so, what is the threshold for the restricted speed), and also assess risk-reduction alternatives.

5.2. PTC cyber security

Cybercrime is a growing threat to infrastructure. Wilson (2003) found that persistent computer security vulnerabilities may expose U.S. critical infrastructure and government computer systems to possible cyber attacks by terrorists, affecting the economy or other areas of national security. The United States and international community have taken steps to prevent cybercrime, but the data suggest that computer attacks will become faster, more numerous, and more sophisticated (Rollins and Wilson, 2007).

The risk of cyber attacks on railroads has been mentioned in several studies (Wilson, 2003; Hartong, 2009; APTA, 2013; Bloomfield et al., 2016). In the past, train control systems did not have to communicate with each other, so direct connections were used (such as one wire connecting to a device without shared communications). Modern railroad communications are digitally connected via Ethernet, Transmission Control Protocol/Internet Protocol (TCP/IP), or a similar networking standard. APTA (2013) pointed out that this standardization introduces new capabilities but also risks. The cyber-security risk is relevant to PTC systems, which involve a complex communication network and a large number of complex digital components.

Fortunately, few records show significant cyber attacks in the railroad industry to date, although historic disruptions in railroad services indicate potential for substantial adverse impacts (Weinstein and Clower, 1998). On August 21, 2003, MARC Commuter and CSX freight rail service experienced cancellations and delays of up to 24 h when a virus disabled the computer systems at the CSX Transportation headquarter in Jacksonville, Florida (Wilson, 2003). Although this was not the result of any deliberate attack, it highlights the potential for considerable damages and losses. A cyber attack on a PTC system could be catastrophic if it affected commuter trains or freight trains transporting hazardous materials.

There has been some prior research on railroad cyber security. Goel et al. (2014) focused on the security of the WIU network that can provide sensory information about the status of signals, switches, and other trackside devices. A prototype of the enhanced WIU security protocols is designed and provided in the deliverable prepared by Goel et al. (2014). Bloomfield et al. (2016) and APTA (2013) studied cyber-security issues related to Britain's rail using ERTMS and U.S. transit agencies using CBTC, respectively. They found that the approaches to cyber security by control systems are different from those by business systems. From a business perspective, traditional cyber security threats concern information integrity, confidentiality, and privacy. For railroads, loss of integrity or availability may result in accidents or incidents. Prior research (e.g. Hartong, 2009; APTA, 2013; Bloomfield et al., 2016) provided some insights in the development of cyber defense in train-control systems. However, more research into the cyber security of PTC and other relevant connected railroad systems is needed. This research can identify the communication vulnerabilities in PTC systems as well as cyber-security techniques to keep nationwide PTC systems operational and secure throughout their life cycles.

5.3. Broken rail detection and prevention

Signaled trackage uses low voltage, electric current in the rails (known as “track circuits”) to detect the presence of trains on a given section. An important secondary advantage of track circuits is that they enable detection of broken rails, which are the leading cause of major derailments on U.S. railroad mainlines (Liu et al., 2017). According to a previous study (Liu et al., 2012), broken rails were the leading cause of Class I railroad mainline freight train derailments in all speed ranges (0–10 mph, 10–25 mph, 25–40 mph, 40–80 mph). Current regulations (49 CFR 236.1007) state that for passenger rail operation over 60 mph or freight railroad operation over 50 mph, PTC systems should include appropriate broken-rail detection and prevention, or equivalent safeguards. In areas without broken-rail detection, the train speed is limited to 59 mph and 49 mph for passenger trains and freight trains, respectively (49 CFR 236.1005). To satisfy the “equivalent safeguard” requirement, some rail lines may need to keep two signal systems, one for PTC vitality and one for broken rail detection (e.g. employing track circuits). However, this could accrue additional costs for signal system installation and maintenance.

In the absence of track circuits, the railroad industry will need to develop equivalent safeguards in PTC territory. Ultrasonic inspection is one principal technology used by North American railroads to identify certain types of rail defects before they grow large enough to cause a derailment (FRA, 2014a). However, because of technological limitations of current ultrasonic inspection technology, defects of certain types, size, and location may not be detected (Orringer, 1990; Liu et al., 2014). Future research is needed on the use of ultrasonic inspection and other safety measures for preventing broken-rail derailments in the absence of track circuits in PTC territories.

5.4. En route failure of PTC systems

PTC integrates various components and devices through different interface types that can be used for communication. As a system of highly complex technologies, PTC is also subject to potential risk from component failures. There are different levels of en route failure in a PTC system. For example, the wayside signal equipment could fail due to improper configuration or software defects, then the system would not be able to determine the status of the signal. In the event of any component failing, PTC system will inherently respond to minimize the hazard. Current regulations (49 CFR 236.1029) require that a train with an en route failure of its PTC system may proceed at the restricted speed to the next available point where communication or a report can be made to a designated railroad officer of the host railroad. If a block signal system is in operation, the train may operate according to signal indication at the medium speed to the point where a report can be made.

Even at a very low probability, PTC failure could lead to accidents with catastrophic consequences. Hartong et al. (2011) used Functional Fault Trees (FFT) to analyze the potential faults of functional architecture, which may result in system failure. Hartong et al. (2011) pointed out that the access to detailed proprietary system design information from vendors limits analysis, such the ability to identify common failure modes among differing applications. Access to proprietary information and advanced methodology are needed to adequately assess the risk of PTC failure.

5.5. Grade-crossing warning systems

There are approximately 210,000 highway-rail grade crossings in the United States, of which 61% are publicly approachable (FRA, 2015a). Each highway-rail grade crossing represents a potential hazard to highway and railway users. Chadwick et al. (2014) found that highway-rail grade crossing users represented about 30% of all rail-related fatalities in the U.S. Thus, there is a significant need for highway-rail grade crossing safety advancement.

Section 11404 of the FAST Act (Congress, 2015a) required the FRA to conduct a study of the possible effectiveness of PTC and related technologies on reducing collisions at grade crossings. Although PTC systems are not designed to prevent accidents at highway-grade crossings, they can be integrated with highway Intelligent Transportation Systems (ITS) such as Connected Vehicles to reduce highway-rail intersection (HRI) crashes (Peters and Frittelli, 2012; FRA, 2015b, 2016a; 2017c). In the PTC-Connected Vehicle technology, trains and cars will “communicate with” each other, sharing information on location and movement information. Both railroad and highway users could then get advance warning through the interconnected information system. In addition, the FRA (2017c) has worked with various organizations to develop the standards necessary for the deployment of grade-crossing warning systems in both PTC systems and local traffic management systems. In the age of intelligent trains and vehicles, more research is needed to develop and implement optimal ITS technology for grade-crossing safety improvement.

5.6. Emerging big data from PTC-enabled operations

Advances in train control and communication technologies have created opportunities to collect railroad data related to infrastructure and train operations. Advanced analytics of the big-data streams generated in the age of PTC present opportunities to improve capacity and locomotive management, reduce false enforcement, and detect railroad system anomalies. Data mining and advanced analytics are relatively new to the railroad environment. Future research may be needed to determine if these techniques can be used to lower operation costs and enhance the potential safety and operational benefits of PTC.

6. Conclusions

Positive Train Control, an advanced rail safety technology, is designed to mitigate human error and improve operational safety. The U.S. rail industry is devoting time and resources to complete PTC deployment pursuant to federal regulations. Challenges to implementation include interoperability, technological complexity, and resource constraints. Several critical issues and knowledge gaps in the age of PTC were identified. These include train safety under restricted speeds, cyber security, safety detection of broken rails in PTC territories, en route failure of PTC systems, grade-crossing protection coupled with connected vehicle technologies, and opportunities for leveraging PTC-generated big data. The cyber-physical inter-connections among infrastructure systems, control centers, and trains create new challenges and opportunities. To this end, more collaboration among the industry, government regulators, and academic researchers is needed to develop policies and practices that can optimize the use of PTC technology and advance rail safety.

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References

American Public Transportation Association (APTA), 2013. Securing Control and Communications Systems in Rail Transit Environments. (Washington, DC).
American Public Transportation Association (APTA), 2015. Positive Train Control: an Assessment of PTC Implementation by Commuter Railroads. (Washington, DC).
Amtrak (National Railroad Passenger Corporation), 2018. Oversight of positive train control implementation in the United States. Testimony by Richard Anderson before the United States House of representatives. In: Committee on Transportation & Infrastructure, and Subcommittee on Railroads, Pipelines, and Hazardous Materials.
Anderson, D., 1995. Study of the Sensitivity of Predicted Stopping Distances to Changes to Input Parameters. Transportation Technology Center, Association of American Railroads, Pueblo, Colorado.
Association of American Railroads (AAR), 2011. Positive Train Control. (Washington, DC).
Association of American Railroads (AAR), 2014. PTC Implementation: the Railroad Industry Cannot Install PTC on the Entire Nationwide Network by the 2015 Deadline.
Association of American Railroads (AAR), 2017. Positive Train Control. (Washington, DC).
Bloomfield, R., Bendele, M., Bishop, P., Stroud, R., Tonks, S., 2016. The risk assessment of ERTMS-based railway systems from a cyber security perspective: methodology and lessons learned. Lect. Notes Comput. Sci. 9707.
Chadwick, S.G., Zhou, N., Saat, M.R., 2014. Highway-rail grade crossing safety challenges for shared operations of high-speed passenger and heavy freight rail in the U.S. Saf. Sci. 68, 128–137.
Code of Federal Regulations (CFR), 2011. Title 49 Code of Federal Regulations. Part 229, 234, 235, 236.
Congress of the United States of America, 1966. An Act To establish a Department of Transportation, and for other purposes. Washington DC, Public Law 89–670.
Congress of the United States of America, 2008. Rail Safety Improvement Act. Washington DC, Public Law, 110–432.
Congress of the United States of America, 2015a. Fixing America's Surface Transportation Act (FAST Act). Washington DC, H.R. 22.
Congress of the United States of America, 2015b. Positive Train Control Enforcement and Implementation Act of 2015 (PTCEI Act). Washington DC. H.R. 3651.
Dingler, M.H., Lai, Y.-C., Barkan, C.P.L., 2010. Effects of communications-based train control and electronically controlled pneumatic brakes on railroad capacity. Transport. Res. Rec. J. Trans. Res. Board 2159, 77–84.
Federal Railroad Administration (FRA), 1980. Accident/incident Bulletin No. 49, Calendar Year. U.S. Department of Transportation, Federal Railroad Administration, Washington, D.C, pp. 1981.
Federal Railroad Administration (FRA), 2009. Positive Train Control Systems Economic Analysis. U.S. Department of Transportation, Washington, DC.
Federal Railroad Administration (FRA), 2010. Positive Train Control Systems. Final Rule, 75 Federal Register 2597.
Federal Railroad Administration (FRA), 2012. Report to Congress on Positive Train Control Implementation Status, Issues and Impacts. U.S. Department of Transportation, Washington, DC.
Federal Railroad Administration (FRA), 2014a. Track Safety Standards; Improving Rail Integrity. 79 Federal Register 4233.
Federal Railroad Administration (FRA), 2014b. Positive Train Control Systems. Final Rule, 79 Federal Register 49693.
Federal Railroad Administration (FRA), 2015a. Office of Safety Analysis 3.01 –Accident Trends – Summary Statistics. http://safetydata.fra.dot.gov/officeofsafety/publicsite/summary.aspx.
Federal Railroad Administration (FRA), 2015b. Highway-rail Intersection Crash Taxonomy for Connected Vehicle Safety Research. U.S. Department of Transportation, Washington, DC.
Federal Railroad Administration (FRA), 2016a. Federal Railroad Administration Status Update on Positive Train Control Implementation. U.S. Department of Transportation, Washington, DC.
Federal Railroad Administration (FRA), 2016b. PTC statutory timeline. Retrieved from;. https://www.fra.dot.gov/Media/File/0972.
Federal Railroad Administration (FRA), 2016c. Positive Train Control Systems. Final Rule, 81 Federal Register 10126.

Federal Railroad Administration (FRA), 2017a. PTC implementation status by railroad. Retrieved from: https://www.fra.dot.gov/app/ptc/.

Federal Railroad Administration (FRA), 2017b. Positive train control. Retrieved from: https://www.fra.dot.gov/ptc.

Federal Railroad Administration (FRA), 2017c. Intelligent grade crossing. Retrieved from: https://www.fra.dot.gov/Page/P0309.

Federal Railroad Administration (FRA), 2017d. About FRA. Retrieved from: https://www.fra.dot.gov/Page/P0002.

Goel, R., Wijesekera, D., Bondi, A.B., 2014. Identity Management for Interoperable PTC Systems in Bandwidth-limited Environments. The Final Report, Part 1 (of three parts) Introduction to The Project And Performance Studies.

Government Accountability Office (GAO), 2013. Positive Train Control: Additions Authorities Could Benefit Implementation. Washington, DC, GAO-13–720.

Government Accountability Office (GAO), 2015. Positive Train Control: Additional Oversight Needed as Most Railroads Do Not Expect to Meet 2015 Implementation Deadline. Washington, DC, GAO-15–739.

Hartong, M., 2009. Secure Communication Based Train Control (CBTC) Operations. PhD Dissertation. George Mason University, Fairfax, VA.

Hartong, M., Goel, R., Wijesekera, D., 2011. Positive Train Control (PTC) Failure Modes. J. King Saud Univ. Sci., vol. 23 (3), 311–321.

Lee, H.H., Mahony, I.G., 2017. Positive Train Control: Roadblocks to Interoperability. Holland & Knight LLP, New York City.

Liu, X., Saat, M., Barkan, C., 2012. Analysis of causes of major train derailment and their effect on accident rates. Transport. Res. Rec. J. Trans. Res. Board 2289, 154–163.

Liu, X., Lovett, A., Dick, T., Saat, M.R., Barkan, C.P.L., 2014. Optimization of ultrasonic rail-defect inspection for improving railway transportation safety and efficiency. J. Transport. Eng. 140 (10) 04014048.

Liu, X., 2015. Statistical temporal analysis of freight-train derailment rates in the United States: 2000 to 2012. Transport. Res. Rec. J. Trans. Res. Board 2476, 119–125.

Liu, X., Saat, M.R., Barkan, C.P.L., 2017. Freight-train derailment rates for railroad safety and risk analysis. Accid. Anal. Prev. 98, 1–9.

Moore Ede, W.J., Polivka, A., Brosseau, J., Tse, Y., Reinschmidt, A., 2009. Improving enforcement algorithms for communications-based train control using adaptive methods. In: Proceedings of the 9th International Heavy Haul Conference – Heavy Haul Innovation and Development, Shanghai, China, pp. 722–727.

National Transportation Safety Board (NTSB), 1991. Most Wanted List. pp. 1990–1991 (Washington, DC).

National Transportation Safety Board (NTSB), 2010. Safety Recommendation Report: Collision of Metrolink Train 111 with Union Pacific Train LOF65-12, RAR1001. (Washington, DC).

National Transportation Safety Board (NTSB), 2012. Safety Recommendation, R-11-6 and -7. (Washington, DC).

National Transportation Safety Board (NTSB), 2017a. Amtrak Train Collision with Maintenance-of-way Equipment, Chester, Pennsylvania, RAR1702. Washington, DC.

National Transportation Safety Board (NTSB), 2017b. Railroad Accident Brief: Collision of Two Union Pacific Railroad Freight Trains, Texarkana, Texas, RAB1708. (Washington, DC).

National Transportation Safety Board (NTSB), 2018a. Preliminary Report Railroad Amtrak Passenger Train 501 Derailment DuPont, Washington December 18, 2017, RRD18MR001. (Washington, DC).

National Transportation Safety Board (NTSB), 2018b. Railroad Accident Brief: Long Island Rail Road Passenger Train Strikes Platform in Atlantic Terminal, RAB1802. (Washington, DC).

Nast, T., Baker, J., Ramos, A., 2016. Positive Train Control Desense Mitigation Test: Research Phase 1 (No. DOT/FRA/ORD-16/15). United States. Federal Railroad Administration. Office of Research, Development, and Technology.

Orringer, O., 1990. Control of Rail Integrity by Self-adaptive Scheduling of Rail Tests. DOT/FRA/ORD-90/05. Federal Railroad Administration, Washington, DC.

Pascoe, R.D., Eichorn, T.N., 2009. What is communication-based train control. IEEE Veh. Technol. Mag. 1556–6072, 16–21 December 2009.

Peters, J.C., Frittelli, J., 2012. Positive Train Control: Overview and Policy Issues. (Congressional Research Service).

Petit, W.A., 2009. Interoperable positive train control. IEEE Veh. Technol. Mag. 4 (4), 27–34.

Railroad Safety Advisory Committee (RSAC), 1999. Report of the Railroad Safety Advisor Committee to the Federal Railroad Administrator: Implementation of Positive Train Control. (Washington, DC).

Rollins, J., Wilson, C., 2007. Terrorist Capabilities for Cyberattack: Overview and Policy Issues. Congressional Research Service. Order Code RL33123.

Transportation Economics & Management Systems Inc, 2017. The Path to Vital PTC and to Operational Impacts for the Railroad Industry. (Presentation at the Transportation Research Board Annual Meeting, Washington, DC).

Thurston, D.F., 2004. Signaling and capacity through computer modeling. In: Proceedings of International Conference on Computer Modeling for Rail Operations, Delray Beach.

The United States Department of Transportation (USDOT), 2017. Fiscal Year 2018 Budget Highlights. (Washington, DC).

Van Dyke, C., Case, R., 2010. Commercial Benefits of Positive Train Control. Oliver Wyman.

Van Dyke, C., 2010. Impacts of positive train control & implications for further research. In: Presentation at the INFORMS Annual Meeting, Austin.

Weinstein, B., Clower, T., 1998. The Impact of the Union Pacific Service Disruptions on the Texas and National Economies: an Unfinished Story. Railroad Commission of Texas. University of North Texas Center for Economic Development and Research.

Wilson, C., 2003. Computer Attack and Cyber Terrorism: Vulnerabilities and Policy Issues for Congress. Congressional Research Service, Order Code RL32114.

Young, J., 2016. The Complexities and Challenges of Positive Train Control. State of the Industry Reports, (Chapter 3). Association of American Railroads, Washington, DC.

Zhao, Y., Ioannou, P., 2015. Positive train control with dynamic headway based on an active communication system. IEEE Trans. Intell. Transport. Syst. 16 (6), 3095–3103.