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Technical and Safety Evaluation of the Southern California Regional Rail Authority Positive Train Control Deployment Project: Challenges and Lessons Learned

JULY 2017

FTA Report No. 0112
Federal Transit Administration

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U.S. Department of Transportation
Federal Transit Administration

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Metric Conversion Table

SYMBOL	WHEN YOU KNOW	MULTIPLY BY	TO FIND	SYMBOL
LENGTH				
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
VOLUME				
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liter	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
NOTE: volumes greater than 1000 L shall be shown in m^3				
MASS				
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
TEMPERATURE (exact degrees)				
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C

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ABSTRACT

Positive Train Control (PTC), often referred to as Communication Based Train Control (CBTC), has been on the National Transportation Safety Board's (NTSB) "Most Wanted List of Transportation Safety Improvements" for several decades as a safety-enabling system. The Rail Safety Improvement Act of 2008 mandated its implementation after the September 12, 2008, Chatsworth, California, collision between trains from the Southern California Regional Rail Authority (SCRRA or Metrolink) and Union Pacific. SCRRA has undergone substantial challenges to integrate PTC into its operations. This report investigates the multilevel challenges—technological, human, organizational, and systematic—that SCRRA faced implementing the new technology as well as many of the lessons the railroad industry can learn from these challenges.

Technology alone cannot ensure safety, but a properly-implemented PTC system can develop and promote high reliability practices that enable safe operations throughout an organization. The report examines interactions among the numerous Systems of Systems for their impact on successful PTC implementation.

EXECUTIVE SUMMARY

On September 12, 2008, a Southern California Regional Rail Authority (SCRRA or Metrolink) passenger train collided head-on with a Union Pacific freight train in the Chatsworth District of Los Angeles, resulting in 25 deaths and 135 injuries (46 critical). Spurred by this and similar incidents, Congress passed the Rail Safety Improvement Act of 2008, which mandated most US railroads to implement Positive Train Control (PTC). PTC technologies use automation to eliminate human errors causing train-to-train collisions, over-speed derailments, and safety risks directly observable by central dispatching offices.

SCRRA took early initiative after the passage of the act to implement PTC on all line segments where they conducted passenger operations and to establish itself as a rail safety leader. A partnership between Rail Safety Consulting, LLC and the University of Southern California (USC) studied SCRRA's PTC implementation process to evaluate current PTC technology and document deployment challenges and lessons learned.

Integration and field testing PTC system components and obtaining the necessary radio spectrum were a particular challenge to SCRRA. Both challenges are identified as issues plaguing PTC implementation throughout the rail industry by the US Government Accountability Office (GAO) [12] and the Federal Railroad Administration (FRA) [13] in 2015.

To implement its PTC system successfully, Metrolink needed to replace and overlay different parts of its existing operational systems. Locomotives required new hardware and software to communicate with the dispatching software via a back office server (BOS). Computer-aided dispatch (CAD) software and hardware were replaced because the legacy system could not be upgraded to accommodate PTC operability (which ultimately resulted in two vendor changes). SCRRA constructed a new hardened operations facility for day-to-day operations because the existing one was insufficient. The entire rail network map needed calibration to ensure accuracy for PTC operations. SCRRA bought simulators to train locomotive engineers on PTC. Finally, acquiring the necessary 220 MHz radio spectrum bandwidth required considerable time, including more than five years of litigation, during which time the PTC–220, a Class 1 company, leased the spectrum to SCRRA.

During the switchover to the new system, SCRRA reported 90% of successful overall runs operating PTC from June 2015 to February 2017. It also established new safety checks and procedures using PTC-generated data, train operator input, and data analysts as part of its new troubleshooting procedures, with included potential hazard identification.

A very real temptation to believe PTC technology a panacea, a cure-all for rail safety was noted, but, hypothetically, PTC technology can improve rail operational safety and capacity as long as it enables high reliability principles and reinforces existing rail safety practices. This includes a very real need to change the current "blame game" culture often noted in the rail industry such that daily operations consider the concerns and experiences of people on the line. To ensure high reliability operations, factors such as motivation, personality (temperaments), moral standards, and working culture should be considered. As was found, working environments that fail to consider these factors prove caustic and inevitably result in disaster.

Although PTC is a new technology, the aviation industry provides critical lessons that the rail industry would be wise to heed. Integrating automation designed to improve safety can sometimes cause accident if operators do not understand its abilities and limitations well. Five basic hallmarks of high reliability organizations that enable safety practices were identified: preoccupation with failure, reluctance to simplify interpretations, sensitivity to operations, commitment to resilience, and deference to expertise. Additionally, five organizational processes that are useful for developing high reliability practices were identified: developing a system of process checks to spot expected and unexpected safety problems, establishing reward systems to incentivize proper individual and organizational behavior, avoiding degradation of current processes or inferior process development, developing a good sense of risk perception, and creating a good organizational command and control structure.

To achieve such fundamental elements of rail (system) safety, the industry must realize that systems such as PTC are very rarely the sum of their parts. Technology and human workers cannot integrate successfully unless there exists a deep respect for the complexity of systems of systems, including how legacy practices must evolve to ensure positive change. Such systems operate and manage themselves independently, evolve over time into their roles within larger systems, and are often geographically-distributed.

The task of PTC integration into the existing rail infrastructure epitomizes the concept of a system of systems because of the massive amount of cooperation needed among Class 1 and passenger rail companies, federal agencies, and vendors, to name a few. The US Government Accountability Office (GAO) [12] and the Federal Railroad Administration (FRA) [13] both noted problems in their 2015 report that appear directly attributable to system of systems complexities—for example, difficulties obtaining approval from various federal agencies for critical PTC components.

To achieve better system of systems performance, the industry must establish good feedback loops that provide information and enable wise decision-making that provides stability and growth while avoiding inadvertent resistance to change and inevitable system collapse. The SCRRA has shown glimpses of this in how its working culture has evolved to troubleshoot problems with its PTC system collaboratively among locomotive engineers and computer engineers. Therefore, as long as the industry can maintain proper non-conflicting directives that do not threaten sustainable behavior by overriding all other priorities, e.g., using on-time performance as a safety metric, the industry as a whole will tend towards a self–organizing, resilient equilibrium that autonomously achieves good performance.

SECTION 1

Introduction

The Rail Safety Improvement Act of 2008

Since the early 1990s, the National Transportation Safety Board (NTSB) has listed Positive Train Control (PTC) among its "Most Wanted List of Transportation Safety Improvements" [1, 2]. On October 16, 2008, the Rail Safety Improvement Act of 2008 (RSIA08) [3] was enacted. Section 104 of the law mandates that all "intercity rail passenger transportation or commuter rail passenger transportation" and "railroads with tracks over which 5,000,000 or more gross tons of railroad traffic is transported annually" must implement a reliable, functional, and interoperable PTC system to prevent:

- train-to-train collisions
- over-speed derailments, including derailments related to railroad civil engineering speed restrictions, slow orders, and excessive speeds over switches and through turnouts
- incursions into established work zone limits without first receiving appropriate authority
- movement of a train through a switch left in the improper position

RSIA08 required each Class I freight and commuter passenger service to equip its lines progressively with a Federal Railroad Administration (FRA) certified PTC system on or before December 31, 2015. This deadline was delayed to December 31, 2018, by the Surface Transportation Extension Act of 2015 (H.R.3819) and the Positive Train Control Enforcement and Implementation Act of 2015 (H.R.3651). This new requirement to implement an interoperable PTC System on a national basis has triggered the largest and most significant federally-mandated railroad safety endeavor since the Interstate Commerce Commission required installation of automatic train stops in the early 1920s. The Fixing America's Surface Transportation (FAST) Act of 2015 encouraged further studies on the effectiveness of PTC and related technologies on reducing collisions at highway-rail grade crossings. The FRA also has developed rules to define criteria for passenger and freight rail lines to ensure PTC technology performs as intended.

SCRRA PTC Implementation – Background

SCRRA System Overview

The Southern California Regional Rail Authority (SCRRA or Metrolink) was formed in 1991 as a Joint Powers Authority (JPA) comprising five county transportation planning agencies to plan, design, construct, and operate a regional transit service throughout the Southern California region [5]. It is governed by an 11-member board composed of representatives from each of the five counties in the region, as well as ex-officio members from the San Diego Association of Governments, the Southern California Association of Governments, and the Secretary of Business, Transportation, and Housing for the State of California. In October 1992, the rail system commenced provision of commuter services, linking communities to employment and activity centers in Los Angeles, Orange, Riverside, San Bernardino, and Ventura counties [5].

The system currently includes 7 lines spread out over 6 Southern California counties and 55 stations and serves 40,000 passengers per day. SCRRA conducts approximately 500 daily SCRRA commuter, Amtrak inter-city passenger, and BNSF/UPRR freight trains [6]. Traffic density varies from more than 40 to 100 daily mixed-freight/commuter/inter-city passenger train moves depending on the line segment. It has in excess of 450 signal locations with 100-plus control points and more than 300 at-grade crossings and is responsible for maintaining 331 track miles and 230 route miles while operating over an additional 123 shared miles. A summary system map is shown in Figure 1-1, and representative trains are shown in Figure 1-2. As of August 2016, SCRRA maintains a fleet of 95 locomotives (52 owned, 43 leased) and 260 commuter rail cars (90 cab cars, 170 coaches) [7]. Trains vary in length from 3 to 6 cars, are diesel locomotive-hauled, and operate in a push-pull mode, with a cab car in the front of the trainset used in the push mode.

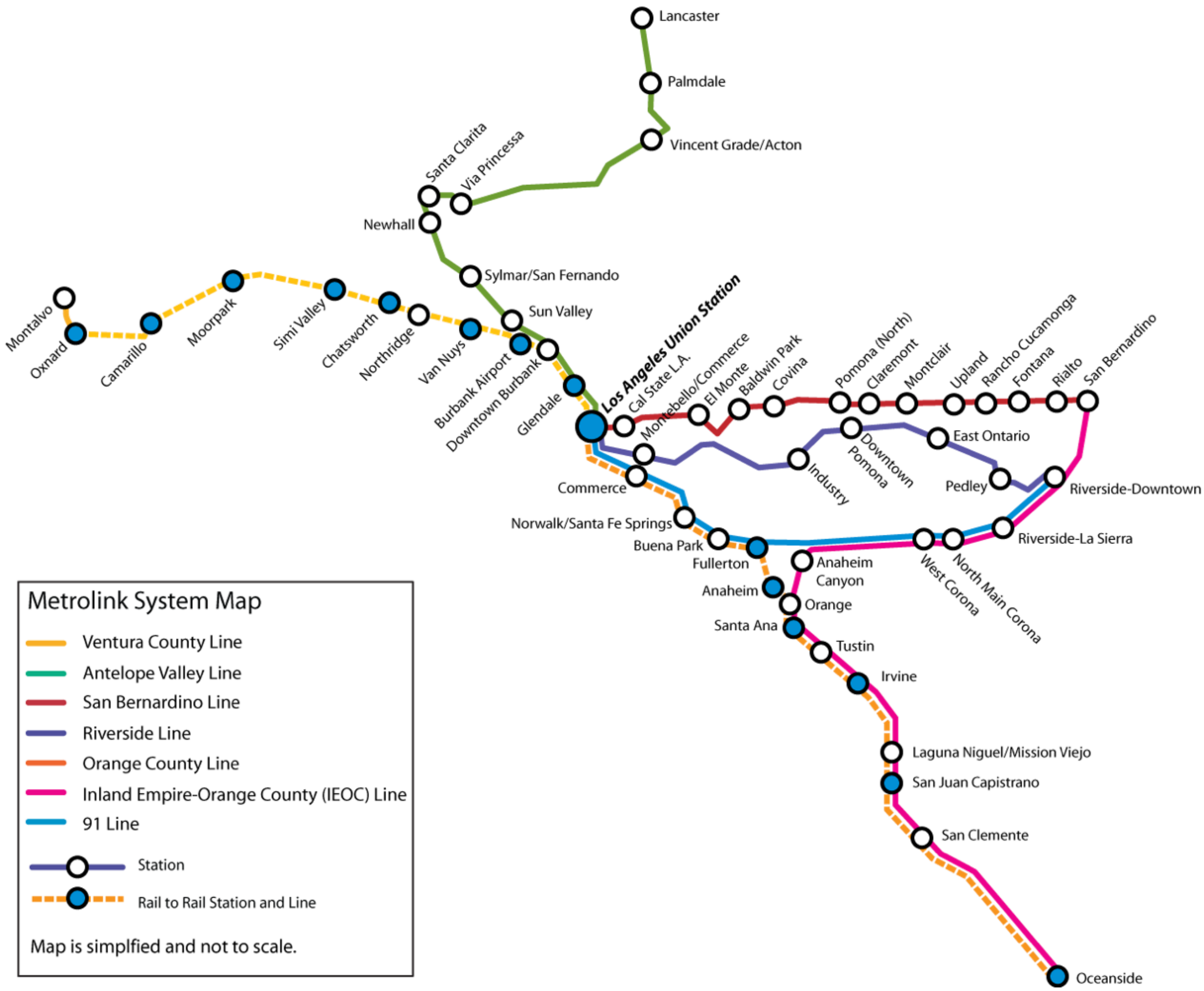


Figure 1-1

Metrolink summary system map

Source: SCRRA and Creative Commons

Source: Creative Commons

Figure 1-2

Metrolink trains outside Union Station in Los Angeles

Prior to the current deployment, the dispatch method of train operation for the region was through a central dispatch office (Traffic Control/Centralized Traffic Control) under SCRRA's direct jurisdiction and operated under the General Code of Operating Rules. A limited amount of Automatic Train Stop (ATS) augmented this system on 388 route miles of line segments. The centralized office, located in a tilt-up concrete office/warehouse in Pomona, ran a centralized CAD system running Digicon software. Digicon no longer supports its software, as it ceased operations in late 2008. SCRRA chose ARINC to replace its outdated Digicon system, but eventually shifted to Wabtec when deploying ARINC's system proved problematic.

In the current Wabtec system, the code server communicates using ATCS data packets relayed over Ethernet via TCP/IP. The radio communication network uses the existing VHF voice radio and ATCS UHF data communications infrastructure. The existing wayside signal system for train control consists of General Electric Transportation Systems (GETS) equipment.

Summary of SCRRA PTC Implementation Project [4]

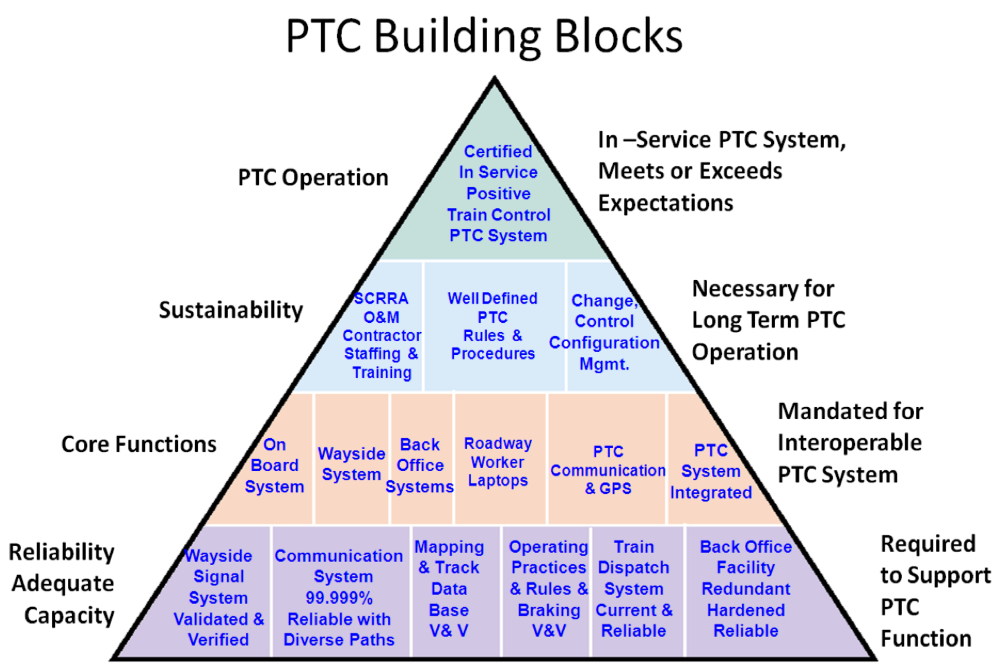
On September 12, 2008, SCRRA commuter train 111 with 222 people on-board collided head-on with Union Pacific freight train LOF65-12 on a curved section of single track in the Los Angeles Chatsworth District in the San Fernando Valley. The accident cost 25 lives, and many of the injured were hospitalized for an extended period. The NTSB found that the probable cause of the collision was the failure of the SCRRA engineer to observe and comply with a red signal [8]. The NTSB also noted that the lack of PTC contributed to the accident.

SCRRA responded aggressively to the Chatsworth tragedy by electing to establish itself as a rail safety leader. This included implementing an interoperable PTC system on all line segments where it conducted passenger operations as part of a sustainable, long-term safety solution that would not degrade overall service, performance, capacity, or reliability. Consequently, SCRRA had to assess, validate, and modify its current system assets—track, signals, wire/wireless communication systems and networks, wireless radio spectrum, dispatching system and offices, information technology systems, locomotives, and cab cars—to assure suitability. Moreover, as SCRRA shared tracks with BNSF and UPRR, two major Class I railroads concurrently installing PTC on an accelerated schedule, SCRRA provided a very suitable candidate for observing significant interoperability planning, design, and debugging on a large-scale basis.

Figure 1-3 illustrates SCRRA's derivation of the various elements needed to implement an FRA- certified PTC system fulfilling RSIA08 and Title 49 of the Code of Federal Regulations (49 CFR) requirements. Although relatively self-explanatory, the essential elements are developing base-level components that supported the core functionality for interoperability. However, maintaining a sustainable system required organizational support.

Figure 1-3

SCRRA-derived system view of PTC building blocks that comply with RSIA08 and 49 CFR 236, 229, 234 and 235 requirements



Source: SCRRA [4]

SCRRA's existing wayside signal system comprises both absolute signals at control points and permissive signals (stop and proceed) at intermediate signals. The PTC system is designed as an overlay on the existing wayside signal system using the Central Traffic Control (CTC) method of operation. Additionally, it was implemented as a safety-critical system designed and implemented to follow the standards and guidelines established by the Interoperable Train Control (ITC) Committee, composed of the four largest US freight railroads, BNSF, CSX, NS, and UPRR [9]. SCRRA's goal is a system that will provide a fail-safe response to system vulnerabilities such as the loss of communication of vital data. The Association of American Railroads (AAR) has adopted this standard.

SCRRA elected to implement an ITC-compliant version of PTC currently known as Interoperable–Electronic Train Management System® (I-TMS®), formerly known as Vital-Electronic Train Management System (V-TMS®) [10]. In addition, and concurrent with implementation of the PTC System, SCRRA replaced its previous CAD system with a new system. The new CAD system includes both a primary and secondary redundant/backup system. SCRRA also included within its scope a new hardened building to house the PTC, primary CAD, and communication command and control systems and the personnel associated with supervising, operating, and maintaining the critical train control and operation functions.

The major hardware/software components of the SCRRA PTC system are:

- back office PTC server system
- on-board system components
- wayside signal systems
- communication network components
- network management systems
- employee-in-charge communications
- PTC compatible computer-aided dispatching system

A communication network links wireless-equipped trains (on SCRRA tracks), wayside, office, and on-board elements. Dispatchers relay movement authority through the CAD via the central office, which is additionally communicated to wayside systems that maintain communication links to PTC-equipped trains. Movement authority consists of a safe point to which a train can travel—for example, an absolute signal displaying a stop. This information is transmitted from the CAD via the central office to on-board PTC equipment, which enforces the stop, as well as other constraints between the train's current position and the limit of the movement authority, including all speed restrictions, both permanent and temporary.

Preparing SCRRA system assets for a PTC system and supporting the system after implementation involved numerous major tasks:

- Rail corridor/track mapping and PTC database development
- General signal system assessment (including validation of all signal systems aspect strings)
- Selective relocation of signals
- Selective removal of unused turnouts and installation of derails interconnected to the signal system
- Selective enhancement of the SCRRA communication system to support PTC
- Conduct of system rail operational analysis to validate PTC communication messaging loads and passenger/commuter train braking algorithms
- Securing and hardening Train Control Operations Support Facility

Figure 1-4 is a high-level depiction of Metrolink's PTC System.

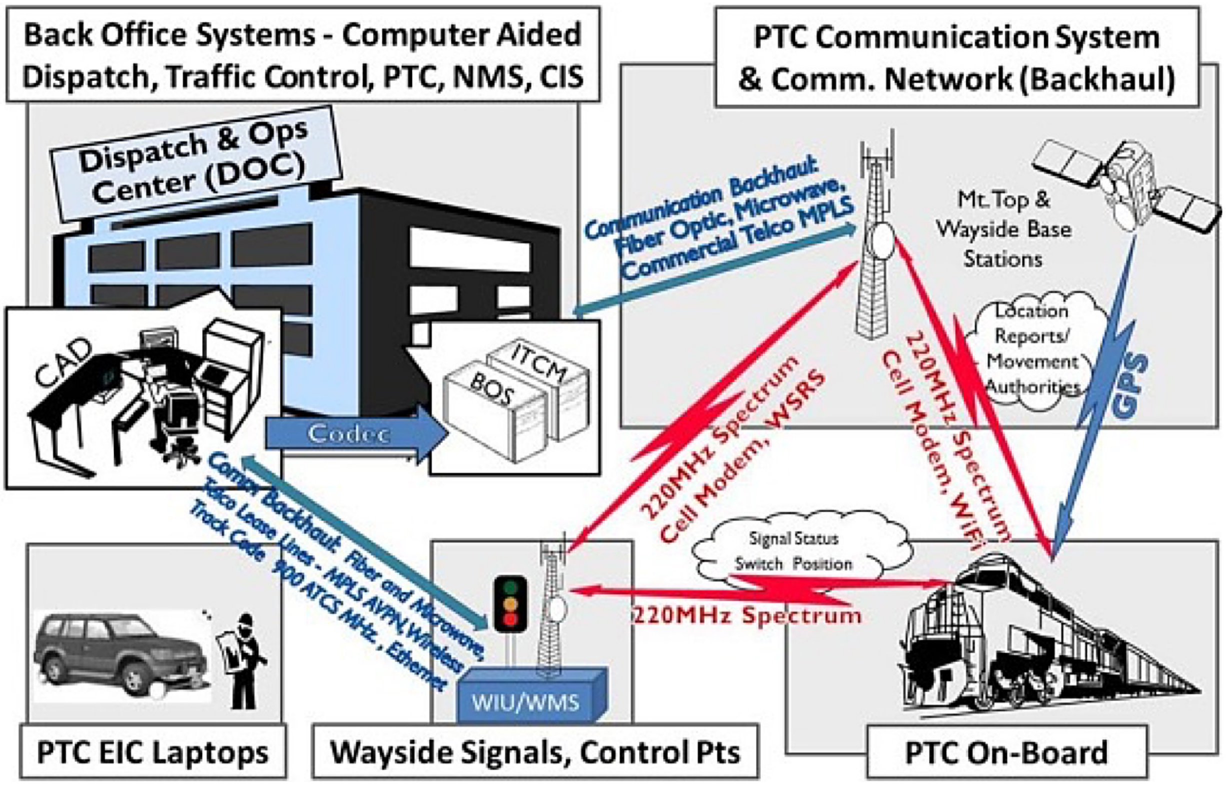


Figure 1-4

Source: SCRRA [4]

High level-depictions of Metrolink PTC system components

USC/RSC Research Project Outline

The University of Southern California (USC), in partnership with Rail Safety Consulting, LLC (RSC) and with the agreement and collaborative support of SCRRA, executed a research study focusing on the implementation of SCRRA's new PTC system. The goal of this research was to evaluate and promote the development of new technologies that will improve the safety and efficiency of rail transit system operation in the US. Focusing on PTC technologies and questions relating to their implementation supports the Federal Transit Administration's (FTA) strategic research goal to improve the performance of US transit systems.

Statement of Problem

This research project focused on the safety and reliability of PTC technology for the commuter rail operating environment and on developing recommendations concerning best practices in the implementation of PTC systems. The research included evaluation of current PTC technology in general and the specific PTC system deployed by SCRRA, documentation of implementation challenges related to the PTC deployment by SCRRA, and lessons learned from these challenges, particularly as they relate to the general experience of commuter rail or regional rail agencies. It also identified the needs for further research in Rail Transit Signal and Control Systems (RTSCS) for commuter and regional rail operations, particularly as these systems relate to PTC objectives.

Research Project Description

A key objective of the USC/RSC partnership was to leverage for gathering lessons learned the combination of USC's extensive research capabilities in control systems, communications architectures, and systems performance with RSC's extensive current participation in many PTC projects, as well as the company's broad knowledge of existing PTC systems and predecessor systems.

The research included the following work items focusing on the study of current technology and decision-making process by SCRRA as the agency implemented a PTC system:

- ***Facilitate implementation of SCRRA PTC system and PTC systems nationally –*** As part of its PTC deployment and system certification process mandated by the RSIA08, SCRRA first submitted its PTC Implementation Plan (PTCIP) to FRA in April 2010. The PTCIP [11] included policy guidelines and technical references Metrolink would use to specify, acquire, install, test, and receive regulatory approval to operate a PTC system on a commuter rail or regional rail transit system. It further documented the details associated with functional requirements, budget and costs, and business agreements related to PTC implementation.

  RSC served as a consultant to SCRRA's lead PTC project contractor for the development of system certification procedures and plans consistent with FRA requirements. RSC's depth of understanding of the overall process of PTC design, application, configuration, and safety programs made it possible to evaluate the work done by other projects and to assist work done by SCRRA. As an active participant in the SCRRA PTC deployment, RSC assured that the USC/RSC team had a firm factual basis for all of the research items as they related to the deployment.

  All railroads governed by FRA PTC regulations must develop and submit complete PTCIPs. Substantive changes must be documented to FRA through a process known as a "Request for Amendment" or RFA. Assistance from the USC/RSC team in this task was limited to advice concerning RFA preparation and revised implementation plan submission. However, RSC reviewed PTCIPs submitted by various rail operators for derivation, data used, calculations made, and conclusions reached. This analysis encompassed business arrangements, financial planning, logistics and scheduling, vendor and PTC technology specification and acquisition, deployment, test, and certification plans.

- ***Evaluate SCRRA PTC performance and capabilities to generalize implications for other systems –*** The primary objective of PTC is to improve the efficiency and safety of a train system using advanced technologies. As new technologies develop, there is always the need to evaluate and test them before widespread application. In this case, SCRRA and its Vendor/Integrator (V/I) Contractor executed the design, provisioning, installation, testing, and integration of the multiple complex systems necessary to provide the grounds for FRA certification. Although the USC team observed many elements of SCRRA's PTC development in an attempt to develop concrete measures and empirical data, it was excluded from many development areas. For example, when attempting to study communication data, attempts to gain access to the data were blocked by a lack of response or resistance by vendors. Moreover, although biweekly update meetings were observed, requests for information often resulted in no response or considerable delays. As a result, the team was unable to observe the effectiveness of PTC in as much detail as originally proposed and did not have access to full–scale system tests. Because of this experience, it must be stressed that future studies such as this one cannot succeed unless investigators receive sufficient cooperation and access during the development process.

SECTION

2

Challenges Identified by SCRRA PTC Implementation Study

In 2015, the US GAO and FRA both issued reports identifying systematic challenges affecting PTC implementations industry-wide. The GAO report [12] identified significant delays caused by:

- developing system components and installing PTC
- system integration and field testing
- FRA resources
- captivity/dependencies
- funding
- radio frequency spectrum and radio wayside poles

The FRA report [13] highlighted similar challenges:

- wireless spectrum availability
- limited number of suppliers of PTC technology
- potential radio interference
- safety plans

SCRRA encountered several of these challenges during its PTC implementation as well as some possible future challenges that may be encountered as it continues to support and refine their PTC system.

Specific Challenges Encountered during PTC Implementation

Transitioning to PTC-compatible CAD System

There was a significant delay involving the transition away from SCRRA's legacy Digicon CAD system. The Digicon system was not compatible with PTC, and there were no plans to make it compatible, so SCRRA contracted with ARINC to update its CAD to a PTC-compatible system. This struggle exemplifies the issues of limited PTC technology suppliers and, to some extent, component development.

SCRRA encountered difficulty implementing the ARINC system that seemed to stem from ARINC's inexperience with heavier rail systems as complex as SCRRA's. ARINC faced considerable technological hurdles with ensuring that its software integrated data streams from the back office, onboard train systems, and wayside components with the dispatching software. This caused delays because it prevented SCRRA from testing other systems that were being developed simultaneously in the lab and deployed in the field. Dispatcher workflow also was disrupted, which increased frustration and distrust of the software. Moreover, the lack of stable software further impacted training throughout the organization, including train operators. As a result, the initial cutover process from Digicon was delayed several times because it was unclear how much operations would be affected by the transition.

System updates often were painstakingly done to individual computers, including updates to the Microsoft Windows system registry. Manually updating the registry is a very delicate process; when done incorrectly, it can cause the system to malfunction, and when the updating process is not automated, the potential for incorrect input grows. In one case, workers were left unprotected in their blocks for nearly 45 minutes because the system had failed to indicate that the block in which they were working was occupied. The cumulative effect, particularly on dispatchers, was a lack of confidence in the ARINC system. After much delay and little progress, SCRRA eventually switched to a Wabtec CAD system.

Integrating and Field Testing PTC System

As SCRRA's PTC system would overlay a legacy system, upgrades would be a considerable expenditure. New system requirements dictated, at the very least, new hardware, most likely on locomotives and cab cars and on the wayside. New system software was required because the existing system software could not support PTC components. Moreover, the existing software vendor was ceasing operations and would not support the transfer of existing rail map data into a new vendor's software. SCRRA, therefore, had to painstakingly verify their physical rail configuration with virtual computer representations using specially outfitted Hi-Rail equipment, as shown in Figure 2-1.

Figure 2-1

Metrolink Hi-Rail equipment outfitted for verifying physical rail configuration

The Back Office Server (BOS), which contains critical information about track geometry, wayside signaling configuration, and permanent speed restriction databases, required new servers and support systems. This was in additional to the already-sizable CAD upgrade requirements. Investigation of SCRRA's previous operations center also found it vulnerable to seismic, fire, and power events and lacking the space and layout to ensure the high reliability and utilization required by PTC. These needs resulted in the construction of a new dispatch/operations center in Pomona. The older facility was moderately hardened and upgraded to act as a hot standby for operations, and as a test facility for new hardware/software. New system training at all levels, from train operators to dispatchers to customer service providers was conducted at the older facility as well [14].

SCRRA personnel noted that service performance significantly declined in the immediate months after the switchover to the new system, but declined to give exact metrics. However, they reported that, overall, 90% of runs with PTC operating were successful without reported incident from June 2015 to early February 2017 [14]. They did not indicate, however, how quickly the success rate improved. In private interviews, SCRRA also reported it established new safety checks and procedures that used PTC-generated data, train operator input, and data analysts to troubleshoot the new system and identify potential hazards.

Obtaining FCC Approval for PTC Radio Tower Installation

SCRRA did not report any appreciable difficulties obtaining approval for its PTC radio tower installations, as it upgraded a fair amount of it established network. SCRRA completed installation of base station sites and towers, including PTC communication equipment in tunnels, by early 2014 and subsequently engaged in extensive testing of overall network performance. Because it was the first regional radio network installed, SCRRA coordinated extensively with the freight railroads that shared their network.

Radio Spectrum Availability

PTC integration required SCRRA to upgrade its communication network. The Interoperable Electronic Train Management System (I–ETMS) operates around the 220 MHz radio spectrum, which is the main communications band.

SCRRA applied to license the upper AMTS bands 217.5 to 218.0 and 219.5 to 220.0 MHz from the secondary commercial spectrum market—in this case, Maritime Communications/Land Mobile, LLC (MCLM). Efforts to obtain the 1 MHz of bandwidth (40 separate 25 KHz channels) from MCLM were significantly delayed by third-party legal action attempting to block the Federal Communications Commission (FCC) spectrum license. In addition, MCLM also had filed for bankruptcy, which required a bankruptcy court ruling.

To mitigate the bandwidth problem, SCRRA considered redesigning the RF network to work with fewer frequencies, but it deemed the option infeasible because of the dense rail traffic and wayside devices in the Los Angeles rail network and urban environment. Instead, SCRRA leased the necessary 220 MHz spectrum from PTC-220 LLC for testing and start-up for five years while litigation continued. PTC-220 is an alliance among the seven Class 1 railroads (CSX, BNSF, UP, NS, KCS, CN, CP) aiming to secure radio spectrum to support PTC interoperability. PTC-220 provides spectrum and leaseholders provide the infrastructure. PTC-220 acquired and licensed 18 broadband 25 KHz channels in the 220 to 222 MHz frequency range. Transportation Technology Center, Inc. (TTCI), a wholly-owned subsidiary of the Association of American Railroads, managed the lease frequency. The bankruptcy court finally ruled favorably at the end of January 2012, but full spectrum acquisition did not occur until September 2016.

Potential Radio Interference

Defining, installing, and coordinating the communication network are critical to ensuring active communications for PTC operations; therefore, it is important to understand how they can degrade and fail. During biweekly progress reports, SCRRA reported no appreciable radio interference issues in the field during testing, and there were no reports of problems with radio interference during revenue service testing.

The research team was unable to use empirical data for radio interference research because of its proprietary nature and difficulties establishing a non–disclosure agreement with SCRRA vendors working with these data. Therefore, the team used statistical methods to examine how stations, trains, train cars and other elements could scatter the communication signals of inbound and outbound trains for what can be considered a worst-case scenario, finding that reliable radio communication could be maintained using robust algorithms [1, 15–18].

Safety Plans

SCRRA submitted its initial PTC safety plan (PTCSP) to FRA as part of certification in October 2015 [19]. FRA granted Conditional PTC System Certification in September 2016, with full certification expected by first quarter 2017 [14]. The research team had no access to this plan and was not consulted in its construction. Developing the plan is understandably difficult, as it requires a functional PTC system that has completed Revenue Service Demonstration.

Potential Future Challenges

Control Center Design

The team was unable to conduct extensive micro- or macro-ergonomic testing of this new control center design due to lack of access. When interviewed about changes to its control center design, SCRRA staff indicated that no extensive studies on the efficacy of the new control center design were conducted, and there were no plans to do so. For security reasons, SCRRA asked that photos not be taken of their control room.

The US GAO noted that some host railroads (those allowing trains from other companies to operate on their tracks) still required tenants to install PTC, despite exemption, because unequipped trains would cause operational/safety concerns even if they ran at reduced speed [12]. In interviews with SCRRA personnel, PTC had reduced throughput during initial runs starting in June 2015. Although it did not report the exact degree of reduction, it did report that from initial deployment to early February 2016, more than 70,000 passenger train trips were operated with full protective collision avoidance and over-speed prevention under PTC, with more than 90% of trips successfully completed [14]. Further analysis of delays showed less than 1% of delayed trips were attributed to PTC. Many were caused by issues with locomotive components or by a cascading effect from earlier delays. However, there is no indication how interactions between the control center and an operational PTC program will affect overall safety. Consequently, FRA should stress micro- or macro-ergonomic studies of new control center design as the PTC system continues to be integrated into normal railroad operation.

Mobile Components

LTK Engineering Services wrote an extensive report for SCRRA detailing the design and testing of the cab display unit (CDU) [20]. CDU designs are based on Federal guidelines for locomotive cab designs [21]. The research team reviewed LTK's report and visited SCRRA's facilities several times during late CDU development. The hardware design was reasonably developed; however, further testing is encouraged to evaluate performance.

Simulator Training

SCRRA uses Corys simulators for training (see Figure 2-1). Instructors establish competency by observing trainees until the instructor judges that performance is acceptable. Evaluators do not consult or analyze data to establish weaknesses/strengths or other potential operator issues. It is recommended that such evaluations use available data more comprehensively to establish more objective competency criteria.

Figure 2-2

Example of Corys simulator at Metrolink

SECTION

3

Lessons Learned

The specific and potential future challenges identified during SCRRA's PTC implementation provide generalizable lessons for both SCRRA's continued support of its PTC implementation as well as for other railroads managing their implementations. The following is a discussion of these lessons learned, drawing on knowledge of high reliability organizations and systems engineering theory.

PTC and High Reliability Organizations

PTC enhances overall system safety by enforcing existing rail practices [22]. It is a predictive collision avoidance system that relies on a network of digital data links to communicate and coordinate the activities of locomotives, wayside units, and the dispatch center. The system monitors train authority to enter a track block by calculating the time before it exceeds its current authority and interceding (reducing speed or stopping) when an engineering fails to take appropriate action. The system does not automate train movements. Rather, it acts like a secondary operator that dynamically enforces existing train authority when an engineer fails to do so. Moreover, by design, it reports when it intervenes so that near-miss events are ideally investigated.

Learning from near-miss events is much less painful than learning from experience. Industries such as aviation and health care have greatly benefited from proactively analyzing and developing measures to address sentinel events and learning from various data sources. This capacity for reflective learning is a hallmark of high reliability organizations (HROs).

SCRRA proactively uses PTC data to identify and analyze hazards and risks and then implements appropriate actions to eliminate/mitigate them, as advocated by FRA's Risk Reduction Program (RRP). SCRRA examines data generated by the PTC system to establish current operating conditions of its fleet. For example, it was noted that patterns emerged regarding certain operators or track sections [23]. Previously, with the absence of data, the only way to identify potential problems was either by limited, ad hoc observations or through painful adverse events. Identifying and analyzing emerging patterns from multiple near-miss events and then developing strategies to address them promises to greatly reduce later incidents, thereby increasing safety.

The process starts when the IT department reviews data retrieved from the PTC system. After review, the IT Department consults with operators and dispatchers to understand why certain identified events occurred. Events range from faulty wayside equipment to operator error. Although anonymous reporting systems such as the Confidential Close Call Reporting System (C3RS) and Clear Signal for Action (CSA) exist for the rail industry, SCRRA's approach is not anonymous. However, instead of placing immediate blame on the locomotive engineer for an incident, SCRRA has developed a culture that encourages self-reporting and collaborative problem-solving that enables engineers and others to do a more comprehensive root-cause analysis to solve the underlying condition(s), as illustrated with a case study provided by SCRRA [23].

The review was more or less self–organized in response to the large data streams that are a natural part of a large network. To filter such data without understanding either content or context risks losing vital clues to the health of the system and potential hidden threats and hazards. For example, the review uncovered a previously-existing, underlying negative feedback loop in which train operators were more concerned about avoiding assignment of blame for events than in being part of a process for identifying root causes and potential mitigations. Only after the IT Department assured train engineers that their participation was invited and could provide valuable context to the data did engineers collaborate rather than act defensively, which resulted in a revised workflow to counter system issues. This cultural shift from "blame and shame" to "collaborative effort" has shown potential for identifying and preempting potential catastrophic events. Moreover, SCRRA has expressed eagerness to share its experiences developing this protocol with the rest of the rail industry.

Principles of HROs

The concept of HROs was developed to avoid or mitigate accidents through proper management of inherent risks. Accidents are practically inevitable within complex systems, because the potential for unexpected interactions are numerous—hence, the inherent potential for risk. "Risk" and "hazard" often are used interchangeably in industry. In actuality, risk is the probability of an occurrence, more formally expressed as: Risk = Probability × Consequence. A hazard is the intrinsic capacity for harm. High reliability theory embraces the potential for accidents, establishes their capacity, and helps make plans to avoid them through organizational design and management.

Work cultures can be described as the default operating environment within an organization. The concept of an HRO was developed to help organizations operating in high–hazard environments maintain low risks while concurrently managing tightly-scheduled operations using five basic organizational principles [24]:

1) Preoccupation with failure.
2) Reluctance to simplify interpretations.
3) Sensitivity to operations.
4) Commitment to resilience.
5) Deference to expertise.

For example, between May 2013 and March 2014, five significant events occurred at Metro-North Railroad, requiring NTSB accident investigations. In a 2014 Special Investigation Report, the NTSB noted that Metro-North's organizational culture significantly lacked all of these principles. In particular, the organization had so greatly overemphasized on-time performance that it became the metric of safety, vastly reducing its ability to comprehend the system health of its network and illustrating a lack of consideration for principles 2 and 3 [25]. In addition, the organization's system safety program plan (SSPP) was so poorly implemented that few employees knew of its existence. Such little regard for operational safety illustrated Metro-North's disregard for potential system failure (principle 1) and the organization's ability to respond (principle 4) [25]. Moreover, SSPP distribution was limited primarily to senior leadership and department heads, offering little, if any, opportunity for employees to provide feedback on the effectiveness of the SSPP in actual practice on the rails (principle 5).

Achieving HRO status is a process of maintaining situational awareness that involves detecting operational anomalies (principles 1, 2, and 3) while properly managing and responding to them (principles 4 and 5). HROs are preoccupied with failure because, even when risks are low and no events have occurred in a long time, the potential for an event is ever-present. HROs are reluctant to simplify interpretations because they respect the delicate balance required to maintain safe operations. HROs are sensitive to operations, maintaining low thresholds for intervention, because they recognize that operations require precise and accurate interactions. Thus, HROs will readily stop to investigate when something seems wrong to prevent potential sentinel events from developing into actual ones.

True commitment to resilience accepts disruption as a natural part of an operational culture, so HROs organically develop contingencies that allow graceful degradation without fundamental breakdowns. HROs also maintain multilevel expertise that defers to the most expert person for a given issue, from the "sharp end" where work is done to the strategic planners at the top of the organizational hierarchy.

These principles require a substantial degree of commitment and resources, but they can foster a culture of trust, shared values, unfettered communication, learning, and continual improvement that nurtures, promotes, and takes advantage of distributed decision-making that can better align an entire organization's resources to deal with adverse events.

Processes for Developing HROs

> "Too often all that stands between one train and the next is the vigilance and dedication to rules and duty of the men and women in the cab of a locomotive, if that fails, almost nothing can reach out and stop a train as it approaches disaster" [26].
>
> *– P.A. Hansen*

Traditionally, train operators are blamed when trains crash because they are considered the only line of defense rather than simply the last line. The HRO process orientation views rail crashes and similar incidents as the outcome of eroded processes that ignored the near-miss precursor events that were most likely identified by others either within the cab/train, at the maintenance yard, or working on the line or even by paying customers. Such indifference usually results from work cultures that overstress productivity, e.g., prioritizing keeping the trains moving over safety.

Despite criticism that the excessively cautious approach of HROs impedes normal operation, high overall operational performance actually is maintained by stressing the need to identify precursors to catastrophic events. HROs recognize that an organization-wide work culture that proactively seeks to reduce event probabilities and mitigate the consequences should they occur can prevent complete system shutdown through more frequent but much shorter proactive measures.

Five organizational processes are noted in the literature as useful for developing HROs [27]:

1) Develop a system of process checks to spot expected and unexpected safety problems.
2) Develop a reward system to incentivize proper individual and organizational behavior.
3) Avoid degradation of current process or inferior process development.
4) Develop a good sense of risk perception.
5) Develop a good organizational command and control structure.

These processes are directed towards establishing an HRO while overlapping the five HRO principles. HROs typically form organically when these principles and processes are allowed to develop symbiotically within an organization.

For example, organizational health can be gauged by a system of regular checks or process audits designed to measure or identify precursors to failures. But to ensure adequate and accurate measures, it is wise to defer to the expertise of those who install, maintain, and operate relevant systems, such as work crews.

Rewards for individual behaviors that foster HRO principles can promote safer work culture as well. Although rewards do not always affect individuals as intended, punishment almost always has a negative effect. The rail industry relies heavily on punitive measures—negative rewards—to ensure compliance. But moral theorists such as Lawrence Kohlberg and Carol Gilligan note that rewards systems that are societal or principle-based often are much more effective in achieving outcomes than rule-based rewards [22, 28].

Avoiding degradation requires vigilance for signs of system failure and a willingness to defer to those who best understand what causes failures and how to neutralize or avoid them. Typically, this also helps develop a good sense of risk perception because these same experts understand and acknowledge which issues are legitimate while also understanding the limits of that knowledge.

Finally, developing a good command and control structure allows HROs to establish strategies that can ensure organizational processes achieve safe, reliable operations. This may seem counterintuitive to the principle of deference to expertise, but it exemplifies strategic expertise versus the tactical expertise of crews and managers lower in the hierarchy. This allows HROs to systematically coordinate multilevel expertise and develop a deep and holistic understanding of how the organization actually functions. During normal operations, HROs retain more traditional hierarchies because standardized safety processes are best when variation is minimal. During crises, however, when conditions are much less certain, HROs often flatten their command structure to allow tactical decisions to be made by those with the relevant expertise, thereby speeding up the decision-making process [29].

Practical Application of HRO Principles and Processes for PTC: Case Studies

Briefly examining case studies of accidents involving trains SCRRA 111 and WMATA 112 in relation to HRO principles and development processes provides a better understand of PTC's role in aiding the development of HROs within the rail industry. This makes it possible illustrate how an operational PTC system could have prevented or mitigated the disastrous consequences of these accidents.

Case: SCRRA Train 111, September 12, 2008, Chatsworth, CA [8]

SCRRA train 111 collided head-on with Union Pacific local freight LOF65 after 111's operator missed and accelerated past the red light at the end of the Chatsworth station. The incident killed 25 people and injured 102, many of them critically.

The NTSB reported 111's operator was texting just prior to the accident and had consistently violated SCRRA's operating rules for electronic devices while on duty. One month prior to the accident, 111's conductor observed the operator using his cell phone while operating the train. The conductor warned the operator about on-duty cell phone use and subsequently reported the incident to a Connex (subcontracted) supervisor. The supervisor later briefed the engineer about on-duty cell phone use, but did not take further action or provide feedback to the conductor. Despite the warnings, the engineer continued his risky behavior, including allowing unauthorized personnel to operate the engine during his shift just days before the accident. No operator monitoring recorders were in the cab; thus, supervising the operator's actions was exceedingly difficult.

Case: WMATA Train 112, June 22, 2009, Fort Totten, Washington, DC [30]

Inbound WMATA Metrorail train 112 struck the rear of a stopped inbound Metrorail train 214 near the Fort Totten station. The impact caused the rear car of train 214 to telescope into the lead car of train 112 by about 63 feet (about 84% of its total length). In total, 9 people were killed aboard train 112, including the operator, and 52 people were transported to local hospitals.

The accident's probable cause was attributed to a faulty track circuit that caused the automatic train control (ATC) system to lose detection of train 214, causing it to transmit speed (proceed) commands to train 112 until impact. The NTSB also cited significant deficiencies in WMATA's overall safety culture that directly contributed to the faulty track circuit being allowed.

Case Implications: HRO Principles and PTC

Principle 1: Preoccupation with failure.

The risks associated with the WMATA 112 and SCRRA 111 crashes had been identified and essentially were ignored at the time of the incidents. In the NTSB report on Fort Totten, more than 30 pages focused on issues of safety culture, 20 of which critiqued WMATA and its safety oversight agency, the Tri-State Oversight Committee (TOC), for its lack of concern regarding proper safety processes for over a decade prior [30]. As the report noted:

> "WMATA does not have a process ... which ensures the timely identification and analysis of hazards. ... Upon questioning, several different **WMATA managers indicated that these issues had been identified already in the accidents** that were being investigated at WMATA. This WMATA approach is reactive and prevents getting value from the proactive aspects of the hazard management process" [30] (*emphasis added*).

Similarly, the NTSB Chatsworth report found the dangers of crews using electronic devices while on duty had been established well before the SCRRA 111 crash. Connex and SCRRA had established rules prohibiting their use by train crews while on duty but had not implemented the means to properly monitor and enforce them [8].

It is interesting to note SCRRA's response immediately after the Chatsworth accident. PTC assumes operators will eventually fail to comply with signals during the normal course of their jobs and, therefore, provides an additional failsafe against such inevitable events. SCRRA's PTC system overlays its existing system, but future rail construction ideally will incorporate the technology directly, as well as add other layers of protection to dramatically increase safety for passengers, operators, and staff. However, SCRRA made significant organizational changes to ensure that safety management was much better integrated with everyday operations beyond PTC implementation. For example, the Safety Department was required to meet with the SCRRA CEO weekly and provide written updates to the SCRRA Board on a monthly basis. Inward and forward-facing cameras were installed on SCRRA locomotives, and regular reviews were planned to better monitor operator compliance. The fleet also was retrofitted with Crash Energy Management (CEM) cab cars and trailer cars to better prepare for the potential of such future incidents [8].

Principle 2: Reluctance to simplify interpretations.

There is no clear indication that either the WMATA or SCRRA accidents resulted from a failure of this principle. However, SCRRA gave significant attention to preventing this problem during its PTC implementation. While monitoring the process, the research team noted that there was a general belief that PTC could be implemented using off-the-shelf equipment. PTC incorporates so many new technologies, however, that it was impossible to predict their interactions. Moreover, many social-technical issues were left unanswered because it was unclear how operators, dispatchers, and other staff would interact with PTC technology.

Although PTC's eventual effects are still unknown, SCRRA has been very diligent in not simplifying its interpretation of the system. For example, it developed a comprehensive version control process that is used to ensure that hardware and software interact properly. It also developed a proactive data review that analyzes PTC logs to better understand how operators are interacting with PTC and where problems may exist. Moreover, the staff made it very clear that they understood that what they did would set the standard for the rail industry, and they wanted to share their experiences. So far, their results appear very promising in this area.

Principle 3: Sensitivity to operations.

As noted, many precursors were ignored prior to both the 2008 Chatsworth and 2009 Fort Totten accidents. Interestingly, in the case of WMATA, there was no connection made between the integrity of the track equipment and what appeared to be the default software state, namely, to proceed when no train is detected ahead. Such a decision was hardly trivial and indicates a preference for continuing operation even when information is unclear or missing. PTC, in contrast, defaults to stopping a train and reporting when there are no clear data to proceed. The latter is much more sensitive to the potential for system failure and, hence, much more conducive to developing an HRO environment.

Principle 4: Commitment to resilience.

In both the WMATA and SCRRA cases, little concern was given to their response to accidents, either proactive or reactive. For example, the aforementioned decision to program the software to proceed even when unexpected events occur, such as a suddenly-disappearing train, illustrates what appears to be an assumption that track circuit signals can always be relied upon when, in fact, that was not the case. A resilient response would be to proceed with caution rather than continue normally. An even more resilient solution would have been to have multiple data sources to ensure backup in the event one signal failed. PTC's design does exactly this by incorporating multiple data sources—GPS, cell signals, Wi-Fi, and wayside markers—in addition to defaulting to a stop state should all data streams be lost.

Another example of resilience is the NTSB's recommendation concerning crash energy management in the case of SCRRA 111. Several deaths were caused by severe trauma due to the sudden negative acceleration during the crash. These deaths were thought to have been preventable had crash energy management been incorporated into SCRRA's coaches.

Principle 5: Deference to expertise.

The failure of track circuit B2–304 to detect WMATA 112 is an interesting study of how not considering technical expertise contributed to an accident. The NTSB report on the Fort Totten accident highlighted that several different technical documents existed addressing track circuit maintenance and testing. These varied in details, but interviews with the construction, inspection, and testing (CIT) supervisor, Red Line ATC mechanics, and the CIT crew leader of the crew that installed the new transmitter impedance bond showed that there was no clear procedure for testing track circuits. Even the procedure developed by the CIT supervisor and the one used by the CIT crew leader varied significantly. As a result, there was no clear-cut consideration of how CIT crews were to ensure that the track circuit was operating properly despite system criticality.

In the case of SCRRA 111, there was more subtle issue with respect to deference to expertise. Although there was no clear indication of a systematic issue with the use of electronic devices by train crews, the inability of conductors and supervisors to monitor engineers for compliance was known. From a human factors perspective, difficulty with monitoring activities, despite its importance, was an indicator of issues faced by those in a position to directly implement the safety policy.

The feedback mechanism for developing a usable PTC interface design on SCRRA locomotives has been a particularly good example of deference to expertise. SCRRA and the project management staff from Parsons have worked actively with senior train operators to ensure that onboard PTC components do not interfere with normal operations. Although field tests must be made to ensure design feasibility, the initial results appear very promising.

Case Implications: HRO Development Processes and PTC

Process 1: Develop a system of process checks to spot expected and unexpected safety problems.

The dangers of operators using electronic devices while operating trains were well known prior to the SCRRA 111 crash. Connex and SCRRA had established rules prohibiting their use by train crewmembers while on duty [8], but there were no means of monitoring operator activities, nor were there adequate feedback mechanisms if prohibited activities were detected. Therefore, while 111's conductor caught the operator using his cell phone by chance and reported it, the extent of his risky behavior, including allowing unqualified individuals to run the train, was not discovered until the NTSB investigation [8].

The case of WMATA 112 provides an even more telling example of an accident caused by deficient system safety checks. The NTSB report on the Fort Totten accident highlighted how faulty testing procedures led to a failure in detecting and fixing a faulty track circuit over a period of about 19 months, with no priority given to developing adequate testing procedures [30]. In both cases, system safety checks or process audits would have better identified the potential for accidents.

A functional PTC system acts much like a second pair of eyes that both monitors operator compliance and intervenes as needed, providing an automated system check against inattentive engineers that warns them about the pending lack of authority to proceed and signals when near-miss events occur that should be investigated. Although this system has not yet prevented an incident, testing has shown it to be very promising in providing process checks for SCRRA's fleet.

Process 2: Develop a reward system to incentivize proper individual and organizational behavior.

> "Disciplinary practices perceived as unfair can motivate individuals to hide safety-related information or adopt behaviors to avoid blame" [30]. As early as 1996, WMATA employees reported "a perceived lack of communication and a sense of information isolation within the organization" [30].

In the cases of both SCRRA 111 and WMATA 112 incentives focused on keeping trains running. For example, WMATA policy prior to the WMATA 112 accident was for operators to use the automated mode to increase performance, i.e., smooth train start/stop/movement leading to more transported passengers. WMATA 214's operator was reprimanded multiple times after he operated in manual mode on several occasions despite his concerns that the ATC system was not operating properly. No attempts were made to investigate whether his concerns were legitimate, even after a near-miss event on June 7, 2005, when two train operators were forced to override the ATC system and manually stop their trains to prevent a rear-end collision [30]. The SCRRA 111 case is not so clear-cut because, whereas policies prohibited using electronic devices while operating trains, enforcement was lax.

Ideally, the PTC system will be used non-punitively to identify the root causes of near-miss events and other potential hazards through analysis of log files. So far, there are indications that SCRRA will be using PTC in this manner.

Process 3: Avoid degradation of current process or inferior process development.

SCRRA 111 can be considered a case of poor employee process development. Both Connex and SCRRA had established rules prohibiting crewmembers from using electronic devices while operating trains. However, monitoring for such activities and enforcement was lax, indicating poor process development in ensuring that operators were attentive to signals, given the increasing potential for distractions that devices such as cell phones posed.

The WMATA 112 case can be considered a case of a degraded automated system and maintenance processes. The degradation of the ATC's ability to detect trains was a key focus of the NTSB's investigation. Although WMATA had attempted to ensure that the system was upgraded, it failed to associate the criticality of the failing circuit with the potential for catastrophic failure. This is illustrated by WMATA's failure to develop proper testing procedures for failing circuits and prioritize correcting problems with them despite near-miss events such as the one in 2005.

PTC offers an interesting challenge. It is designed to avoid collisions when operators do not respond to signals in a timely fashion, but its many components all can degrade. SCRRA, to its credit, has developed an extensive version control system to maintain compatibility of installed PTC components within its track system as well as those that are interoperable with PTC systems operated by other railroad companies on which SCRRA's fleet operate. SCRRA should continue this practice to ensure accidents similar to Fort Totten are avoided.

Process 4: Develop a sense of good risk perception.

Prominent disassociations between sentinel events and the associate risks were evident in the WMATA and SCRRA accidents. For example, in the WMATA 112 case, the bobbing track signal was poorly associated with the risk of a train collision. This is understandable because repairs and maintenance are commonly considered risk-reducing, but only when done correctly. The lack of a working process to detect faulty track circuits illustrates a poor appreciation for system criticality and its risks, especially when considering the 2005 near-miss event. Similarly, although Connex and SCRRA had established a policy prohibiting crews from using electronic devices while on duty, the response to the reported infraction and the steps to monitor and prevent such activity showed a poor appreciation of the potential risk of distraction such devices posed.

Process 5: Develop a good organizational command and control structure.

Command and control consists of five elements:

1) **Migrating decision-making**

This element is related to the principle of deference to expertise. HROs consider the person(s) with the most expertise in a given area to be the best decision-maker. The decision-making process leading to the WMATA 112 accident best illustrates this element. As the NTSB noted [30]:

> "WMATA placed much of the blame for causing and much of the responsibility for preventing accidents on frontline personnel. ... **[P]lacing blame on frontline employees is not likely to improve the safety of the system as a whole."** (Authors' emphasis)
>
> "WMATA does not have a process, including a single point of responsibility, which ensures the timely identification and analysis of hazards. ... [They] were unable to provide a comprehensive matrix or assessment that identified the agency's on-going evaluation and management of its most

> serious safety hazards and concerns. ... WMATA managers indicated that these issues had been identified already in the accidents that were being investigated at WMATA. This WMATA approach is **reactive and prevents getting value from the proactive aspects of the hazard management process."** (Authors' emphasis)
>
> "... [I]t does not appear that there is effective interdepartmental coordination regarding the identification and management of maintenance-related safety hazards. ... Further, ... FTA determined that there is **no formal process for identifying and managing the likely safety impacts of budgetary decisions affecting maintenance."** (Authors' emphasis)

In other words, WMATA had failed to develop a system for strategic decision-making that could establish a proactive organizational safety culture capable of recognizing and responding to the implications of near-miss events like the 2005 near collision. Moreover, because safety decisions remained primarily tactical, the potential lessons learned were effectively lost to the rest of the organization. As a result, hazardous conditions were allowed to persist, nearly assuring similar future events like the Fort Totten accident.

2) Redundancy of people and/or hardware

Redundancy is typically associated with backup systems for critical processes. For example, in both the cases of WMATA 112 and Metrolink 111, the single points of failure were a faulty track circuit and an inattentive operator. WMATA's emphasis on automation effectively removed the redundancy of human intervention, and SCRRA had no backup system at all. PTC provides redundancy by acting like second pair of eyes that warns the operators when they fail to comply and then intervenes by slowing/stopping the train as needed.

3) Macro-management

Maintaining a strategic, big-picture focus is essential for maintaining healthy organizational processes. For example, WMATA's senior management placed all responsibility for improving system safety on frontline employees prior to the Fort Totten crash. Removing senior management from the control loop fundamentally removed WMATA's awareness of overall operational safety [30]. Similarly, at the time of Chatsworth accident, SCRRA's hierarchical structure disallowed any direct interaction between its Safety Department and senior management, namely the CEO [8].

The research team noted the change in macro-management dynamics at SCRRA shortly after the Chatsworth crash. In 2011, the SCRRA CEO solicited the USC Viterbi School of Engineering to develop a two-day instructional course entitled, "Rail System Safety: Safety Culture and Human Performance." As explained, PTC and other safety technologies were simply tools to achieving an end, and he wanted to "bring home the message of safety and how to promote it properly within his organization" by developing a short course that would teach senior management, from frontline operations to customer relations, to develop a safety culture and how to foster it within their respective divisions and throughout the industry.

The course was delivered In August 2011 to overwhelmingly positive feedback. One attendee remarked that it was the first time he had witnessed senior management engaged in such a cross-disciplinary discussion. Those who participated reported that they still invoke the lessons learned from the course. In addition to this course, SCRRA continued to involve USC in planning and executing several Safety Summits with NTSB that focused on how to improve and promote safety culture within SCRRA and throughout the rail industry in the aftermath of the 2008 accident.

4) Formal rules and procedures

Although HROs tend to flatten when the unexpected occurs, well-defined hierarchies still have a place in developing new rules and procedures to face unexpected situations. For example, as noted, prior to the Chatsworth accident, Connex and SCRRA developed a policy against crews using electronic devices while on duty based on device distraction accidents reported within the rail and aviation industries and the public. Unfortunately, they lacked an effective method of compliance as operators monitoring was difficult at best. Moreover, crew motivations apparently lacked a clear connection between accident risks and distractions caused by electronic devices.

5) Training

One of the hallmarks of a safety culture is that it continually learns from a variety of sources. Training often allows organizations to propagate learning to their workers, but its effects vary widely.

It is important and interesting that, in general, the rail industry works hard to prevent accidents, but the push to meet tight schedules often countermands training. This was witnessed in the cases of WMATA and SCRRA. The rail industry appears to spend much less time on systematic safety compared to aviation and health care.

For example, it was surprising that the short course delivered to senior SCRRA management had never been developed before. Feedback from attendees was that tapping the collective expertise of people at all levels of the organization and among different departments was a very useful exercise that drove home the point that safety is an ongoing, organization-wide process. Empowering attendees to offer their own expertise and experiences and allowing them to realize that their voices mattered furthered this process. This feedback indicates that replicating such safety classes would greatly benefit the industry.

PTC System Implementation and Work Culture

One of the deployment's critical concerns is the propagation and sustainability of PTC after initial implementation. For example, the May 12, 2015 derailment of Amtrak Northeast Regional No. 188, in Philadelphia was directly attributed to an over-speed violation that could have been prevented if Amtrak's version of PTC, Advanced Civil Speed Enforcement System (ACSES), had been enabled on the northbound section of the track. Sadly, it was enabled only on the southbound section.

How can total system implementation be developed and sustained using psychological and work culture influences within the rail industry? Answering this question benefits further integration of technologies such as PTC.

Organizational cultures often invite certain outcomes, desirable or not, including types of worker behaviors. Motivational theories can drive organizational cultures but are insufficient to ensure worker compliance, and, in some cases, they can actually cause the unintended effects. Understanding the underlying factors that develop and sustain organizational environments can provide powerful insight into promoting the robust, healthy organizations that are needed to successfully implement new technologies such as PTC. Moreover, incorporating such factors into organizational policies and practice can better use worker abilities [28].

Management typically perceives workers in one of two ways. Theory X hypothesizes that workers are self–serving and inherently lazy, requiring close supervision and regulation. In contrast, Theory Y presents workers as products of their work environment, where humane environments that foster satisfaction for doing a good job develop self-actualization. The Theory X perspective is more often adopted by industry, but monetary incentives and punishments alone were found ineffective around the turn of the 20th century. Thoughtful consideration of individual worker motivations is required. For example, managers often are familiar with Maslow's Hierarchy of Needs [31], which states that humans must satisfy basic needs such as food, water, shelter, and affirmation before they will consider higher ones such as self-actualization and helping others. However, theories such as McClelland's Theory of Needs [32, 33] and Herzberg's Two-Factor Theory of Motivation [34] see workers as having a basic human need for achievement (desire to excel), power (desire to lead), and affiliation (desire for relationships and mutual understanding) or as having extrinsic factors such as working conditions and intrinsic factors such as meaningful work that govern their work habits. It has also been found that personality temperament or types [35] (e.g., action-oriented, methodical, analytical, or feeling-oriented), moral acceptability of action [28] (e.g., rule–based rewards and punishment, social acceptability, internalization of universal principles/guidelines), and organizational cultural dimensions [36] (i.e., power distance, assertiveness, individualism vs. collectivism, uncertainty avoidance, and time orientation) can all have subtle but profound impacts on how workers operate.

Theories presented here can be summarized as a series of questions to facilitate organizational application [28]:

- Motivational theories
  - What motivation drives the organization and worker?
  - Does the organization's motivational strategy, including reward and punishment, correspond to workers' needs and attitudes about work?
  - Do these motivations enable an HRO according to [22]?
- Personality temperaments/types
  - How do the organization and worker perceive and interact with their environment?
  - Does the organizational and worker temperament correspond?
  - Do worker tasks correspond with their temperament?
  - Do these temperaments enable an HRO according to [22]?
- Moral factors
  - What ethical standards restrict the organization and worker?
  - Do the ethical standards of the organization and worker correspond?
  - What is the relationship among industrial regulation / practices, organizational operations, and worker actions?
  - Do these ethical standards enable an HRO according to [22]?

- Cultural dimensions
  – What is the organization's cultural environment?
  – Do these cultural dimensions enable an HRO according to [22]?

These questions encourage building HROs because the end goal is to develop to remove or mitigate risks within rail operations as noted above and in [22].

Linking the organizational theories presented here with HRO principles [22] into a more comprehensive theory and practical application is a logical next step. Further research is also highly recommended to expand and apply these theories and others into a potentially larger unified theory of organizational psychology/culture that can be linked to establishing safe and productive work cultures. A more comprehensive theory that integrates the theories outlined here and correlates them with the potential for certain outcomes could be highly advantageous to the rail industry.

SECTION 4

Systems Engineering

Three variables often are used to understand systems engineering outputs within organizations:

- human workers
- organizational practices
- technology used to achieve desirable organizational outcomes

The HOT (humans, organization, technology) model includes examining these variables, their interactions, and their effects on achieving organizational goals/outcomes. Human workers are agents who operate within the system. Organizations provide the environment within which agents operate, including the rules of the game that enable and restrict agent actions, including interactions with other agents and the organization as a whole. Technology is the means by which outcomes/artifacts are produced.

Systems are rarely the sum of their parts, so the interactions among these variables are as important as the purpose or functionality they are aligned to achieve. Feedback loops, if used properly, can provide system equilibrium or goal-seeking structures that can provide both system stability and growth while avoiding inadvertent resistance to change or system collapse. Feedback loops are typically closed chains of causation that include information, decision–making and physical laws that reinforce or weaken future system interactions.

Resilient organizations are typically self-organizing and tend towards balanced equilibrium based on sustainable behavior. However, organizational priorities can create dominant feedback loops that conflict and/or override others priorities and that force the entire system toward undesirable, unintended outcomes [40].

The International Council on Systems Engineering (INCOSE) defines systems engineering as:

> "… an interdisciplinary approach and means to enable the realization of successful systems. It focuses on defining customer needs and required functionality early in the development cycle, documenting requirements, then proceeding with design synthesis and system validation while considering the complete problem.
>
> "Systems Engineering integrates all the disciplines and specialty groups into a team effort forming a structured development

> process that proceeds from concept to production to operation. Systems Engineering considers both the business and the technical needs of all customers with the goal of providing a quality product that meets the user needs" [37].

Unfortunately, the current rail control system is not part of the national Intelligent Transportation Systems (ITS) architecture, but the US Department of Transportation (US DOT) requirement for a systems engineering analysis for ITS projects funded with the Highway Trust Fund, including the Mass Transit Account, indicates its importance. Such US DOT analyses must [38]:

- Identify portions of the regional ITS architecture being implemented (or if a regional ITS architecture does not exist, the applicable portions of the National ITS Architecture).
- Identify participating agencies' roles and responsibilities.
- Have requirements definitions.
- Analyze alternative system configurations and technology options to meet requirements.
- Have procurement options.
- Identify applicable ITS standards and testing procedures.
- Have procedures and resources necessary for operations and management of the system.

Other than the fact that PTC is not considered part of the US ITS architecture, each of these items applies to the PTC implementation process.

Although rail safety has been highlighted as the driving force behind PTC implementation, other system elements can and will inevitably be affected. At the operational level, PTC potentially affects headway separation, communication models, and overall throughput performance. At a macroscopic level, PTC has the potential to affect safety, efficiency, and organizational practices. These multilevel interactions illustrate the essential role of systems engineering for integrating systems of systems (SoS) such as PTC into the Intelligent Transportation Systems (ITS) of the US.

Systems of Systems Characteristics

Systems of systems share several key characteristics [39] that US rail infrastructure closely follows:

- **Operational Independence of Elements**

  If an SoS is disassembled into its component systems, the component systems must be able to usefully operate independently. SoSs are composed of systems that are independent and useful in their own right. Although the numerous rail organizational entities (e.g., SCRRA and Amtrak), resource providers (e.g., locomotive and car manufacturers, rail equipment providers, etc.), and Federal agencies collaborate, each entity can operate individually and does so on a regular basis. For example, SCRRA regularly operates as an independent rail organization.

- **Managerial Independence of Elements**

  Component systems not only can operate independently, they do operate independently. Component systems are separately acquired and integrated but maintain a continuing operational existence independent of SoS. As noted previously, rail organizational entities operate independently and do so on a regular basis while collaborating with multiple organizations. For example, SCRRA operates simultaneously with Amtrak within the Southern California region while retaining individual ownership of its operations. This includes differing PTC implementations such as BNSF's I-ETMS®, which SCRRA has implemented, versus (ACSES).

- **Evolutionary Development**

  An SoS does not appear fully formed. Its development and existence are evolutionary, with functions and purposes added, removed, and modified with experience and need. The PTC implementation process has necessarily evolved since the passage of the Rail Safety Improvement Act of 2008 because of technological advances and organizational changes. Numerous unforeseen issues have emerged throughout the rail industry during PTC implementation, resulting in delays and requests for extended deadlines. For example, there are cases in which the FCC delayed approval for wayside equipment installations [12]. Unfortunately, many of the delays resulted from confusion about what constitutes a "communication tower" under FCC regulations. Because these PTC wayside towers are usually much smaller, they have much less environmental impact than the large media communication towers that the FCC typically regulates. However, the FCC has made no distinction between the two, nor does it appear it is aware of the difference. This has prompted discussion within the rail industry about how to more effectively deal with this situation.

  Another interesting evolutionary development has been the use of PTC system-generated data, which SCRRA has begun using to troubleshoot and identify potential sources of accidents. The resulting shift in the communication model and feedback loop promises to greatly improve the systems dynamics of the rail industry, including improved safety and efficiency, because it promotes the learning and just culture we noted as key elements of HROs.

- **Emergent Behavior**

  An SoS performs functions and carries out purposes that do not reside in any component system. These behaviors are emergent properties of entire SoSs and cannot be localized to any component system. Principal purposes of the SoSs are fulfilled by these behaviors. Although each rail organization under the RSIA08 mandate is allowed to develop its own PTC implementation, as a whole, the RSIA08 mandate requires certain core functionality that does not reside in any single implementation—for example, the I-ETMS® used by SCRRA and BNSF uses GPS to establish exact position, whereas Amtrak's ACSES uses transducers and track circuits. However, both systems are, by necessity, required to adhere to the larger requirements to quality as PTC compliant.

- **Geographic Distribution**

  The geographic extent of component systems is large. Although "large" is a nebulous and relative concept as communication capabilities increase, at a minimum, it means that components can readily exchange only information and not substantial quantities of mass or energy. The US rail industry and PTC mandate spans most of the North American Continent, which would mostly likely qualify it in this domain.

SoS Domain Ontology

Developing an SoS ontology makes it possible to perform several actions to establish critical system elements. [39] These include:

- Better understanding the structure and interactions of multiple agents (e.g., people, automation, software modules).
- Discerning patterns and trends that identify reusable elements (e.g., knowledge, interaction patterns, and data).
- Making assumptions explicit.
- Separating domain knowledge from operational knowledge.
- Analyzing domain knowledge.

At the heart of the effort is a map to mitigating the inevitable challenges of incorporating technology when its level of maturity is uncertain. In such cases, successful integration into existing systems must be incremental. Incorporating new technology such as PTC into the existing rail infrastructure inevitably requires the implementer to consider the following [39]:

- Multiple, often conflicting objectives
- System environments that are complex, often poorly and /or incompletely specified, and difficult to analyze
- Dynamic interactions
- Different fault types
- New uses, changes, replacements, and reconfiguration

These were particularly critical within the context of PTC implementation because of the technical challenge and need for interoperability among different types of PTC implementations. Several of these issues were observed at multiple levels within SCRRA as it developed its PTC system. One of the more interesting elements during integration was Metrolink's response to using the data generated by the PTC system.

PTC as an SoS

The Rail Safety Improvement Act of 2008, which initiated the spur to implement PTC, requires certain railroads (mostly Class 1 and Passenger) to implement a system that meets four core functionality requirements [3]:

1) Train separation or collision avoidance
2) Line speed enforcement
3) Temporary speed restrictions
4) Rail worker wayside safety

Given the nature of the US railroad infrastructure, achieving such core requirements can be accomplished only by considering the chief characteristic of SoS—the need for collaboration among systems with different owners and governances. Unfortunately, although PTC functionality is well-defined in general, individual implementations are less so, as they are region-specific. The process of developing specifications and the technology to fulfill them requires significant resources and tradeoffs among these systems. In addition, procedural and organizational criteria must be considered, including an understanding of the capabilities and constraints of stakeholders/decision makers at all levels. Finally, as the new system emerges, the knowledge, skills, and experiences needed to operate and maintain the system proficiently must be passed on through training and education.

SCRRA objectives included the safe, efficient delivery of passengers from a point of origin to a destination within their rail system while generating sufficient revenue to allow continued operations. Designated managers and resources allow SCRRA to achieve these objectives. To achieve the RSIA08 mandate, SCRRA needed to collaborate with multiple organizations, including government agencies such as FRA and FTA; other rail organizations such as BNSF, Union Pacific, and Amtrak; and resources providers such as Parsons, Digicon, ARINC, and Wabtec. Each of these organizations has its own objectives, managers, and resources that allow it to retain independent ownership of its own systems, funding, development, and maintenance. Collaboration among these entities must be negotiated for any SoS changes to occur.

The cycle of development, installation, and testing could not be considered independently even if individual components could be swapped. As noted by the

GAO [12] and FRA [13] reports, issues arose dealing with developing, lab testing, installing, integration, and field testing of PTC components, including back-office systems. Ensuring I-ETMS interoperability of PTC systems and components also was indicated, as was obtaining FRA certification and approval of systems and safety plans, including FRA's available resources and timeliness.

SCRRA's very public software vendor switch from ARINC to Wabtec in late January 2014 [41, 42] illustrated the importance of SoS interoperability. Recall the challenges identified previously concerning implementation of the ARINC software. This greatly affected SCRRA's organizational ability to achieve its PTC implementation objective and meet the December 2015 deadline. In contrast, Wabtec better aligned with SCRRA's objectives by virtue of its considerable experience developing a working software system with BNSF, including the working Interoperable Electronic Train Management System.

Although this software vendor issue was one of the most visible challenges faced by SCRRA, it also faced many other difficulties reported by the GAO and FRA reports [12, 13], including difficulties obtaining radio frequency spectrum; system field testing, certification, and approval; and radio interference. Moreover, had SCRRA not been at the forefront of PTC implementation, it likely would have faced considerable issues with funding as well. The takeaway of SCRRA's experiences is the importance of considering SoS elements during PTC implementation.

These challenges with interoperability share several common factors [39]:

- Programmatic – between different program offices
- Constructive – between organizations responsible for creating and maintaining a system
- Operational – between systems
- Syntactic – systems share common communications protocols, data formats/ordering
- Common vocabulary – systems in SoS share common terminology

SCRRA's experiences illustrate the critical need to consider systems engineering during PTC implementation. The issues identified by the GAO [12] and FRA [13] show a commonality with the vast majority of PTC implementers within the rail industry. Therefore, developing a systems engineering approach to the implementation process that considers the interaction/interoperability of SoS in new technology integration is critical. Without it, the ability to adhere to a reasonable schedule and budget while using new technologies in a cost-effective way with well-mitigated risks is jeopardized seriously.

SECTION

5

Conclusion

SCRRA/Metrolink's efforts to implement PTC have proven to be a considerable technical challenge. However, their experiences have been common to the rail industry, including delays with procuring and installing working PTC system components, integrating PTC into functioning workflow processes, and obtaining acceptable radio frequency spectrum. Issues related to core systems and organizational factors have been underreported elsewhere, and these have been our focus.

To address such issues, models such as HOT were used to examine how organizations can and should properly manage the integration of technological systems with human operators to ensure successful and sustainable implementations that achieve their ultimate goals—in this case, improved safety. For example, it was noted that dispatchers needed timely and reliable information to maintain the flow of train traffic effectively and safely. Unfortunately, early versions of the original PTC software gave inadequate consideration to these factors, resulting in an eventual change in the software vendor after considerable development time and expense.

Even more imperative, identified was a need for the rail industry to examine its organizational practices and their effects on safety. The rail industry often has been characterized by the "blame game." In particular, locomotive engineers face heavy–handed sanctions for errors. This was witnessed during the early stages of testing. When the PTC system reported violations, locomotive engineers repeatedly misrepresented their conduct for fear of punishment. This behavior changed only after PTC testing engineers actively solicited feedback about the context of violations and assured locomotive engineers good faith errors would not be punished. By using individual personalities, ethical standards, and motivations—"human factors"—a collaborative culture emerged that organically enabled HRO principles. Locomotive engineers now self–report, more readily identify potential issues, and developed and enacted mitigation strategies. This shift in organizational practice alone promises to improve rail as much as PTC deployment, as it mimics changes in the aviation industry that enabled it to become one of the safety industries in the world today.

Although PTC technology promises to improve rail safety greatly, examples such as the 2009 Fort Totten crash illustrated that it can augment safety only as long as it enables fundamental elements of system safety. Simple "stick or carrot" regulations and feedback most likely will undermine the fundamental safety elements behind PTC, unless the individual ability to contribute to improved safety and overall system reliability by developing a sense of ownership is considered. Hence, whereas PTC can reinforce a positive safety culture, it requires careful consideration of those who work with the technology to assure maximum effectiveness.

ACRONYMS AND ABBREVIATIONS

49 CFR	Title 49, Code of Federal Regulations
AAR	Association of American Railroads
ATC	Automatic Train Control
ATS	Automatic Train Stop
BOS	Back Office Server
C3RS	Confidential Close Call Reporting System
CAD	Computer-Aided Dispatch
CBTC	Communication-Based Train Control
CDU	Cab Display Unit
CEM	Crash Energy Management
CSA	Clear Signal for Action
CTC	Central Traffic Control
FAST	Fixing America's Surface Transportation Act of 2015
FCC	Federal Communications Commission
FRA	Federal Railroad Administration
GAO	Government Accountability Office
GETS	General Electric Transportation Systems
HOT	Humans, Organization, Technology
HRO	High Reliability Organization
ITC	Interoperable Train Control
INCOSE	International Council on Systems Engineering
ITS	Intelligent Transportation Systems
I-ETMS®	Interoperable Electronic Train Management System
Metrolink	Southern California Regional Rail Authority
NTSB	National Transportation Safety Board's
PTC	Positive Train Control
RRP	Risk Reduction Program
RSC	Rail Safety Consulting, LLC (division of TUV Rheinland Mobility)
RSIA08	Rail Safety Improvement Act of 2008
RTSCS	Rail Transit Signal and Control System
SCRRA	Southern California Regional Rail Authority
SoS	System of Systems

SSPP	System Safety Program Plan
USC	University of Southern California
USDOT	US Department of Transportation
V-TMS®	Vital-Electronic Train Management System®
WMATA	Washington Metropolitan Area Transit Authority

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