Preliminary Investigation (PI-0115)

Caltrans Division of Research, Innovation and System Information

Integration of Positive Train Control With Earthquake Early Warning Alert

Requested by
Chad Riding, Division of Rail and Mass Transportation

January 31, 2019

Table of Contents

Executive Summary

Background

Currently, California has three intercity passenger rail lines and five commuter rail systems, and the California High-Speed Rail Authority is constructing a high-speed rail system that will eventually extend from Sacramento to San Diego.

The federal Passenger Rail Investment and Improvement Act of 2008 included a requirement for passenger and major freight railroads to install positive train control (PTC) on most major routes by the end of 2015. A 2010 report published by the U.S. Government Accountability Office (see https://www.gao.gov/new.items/d11133.pdf) described PTC as "a system designed to prevent accidents caused by human factors, including train-to-train collisions and derailments that result from trains exceeding safe speeds. It is also designed to prevent incursions into work zones and movement of trains through switches left in the wrong position." In 2015, Congress extended the deadline for PTC system activation to December 31, 2018. Railroads could also meet the statutory requirements to qualify for an alternative schedule for up to two additional years to complete full implementation.

As California prepares to meet the federal government-mandated installation of a PTC system to improve train safety, Caltrans is also interested in examining the systems and tools available to protect rail infrastructure and operations from earthquakes and seismic activity. Integrating earthquake early warning (EEW) alert systems into PTC has the potential to save lives and protect railroad assets. Caltrans is particularly interested in identifying current efforts to integrate EEW with PTC that could inform a potential pilot project in California that develops and tests an integrated PTC/EEW system.

To gather information in these areas of interest, CTC & Associates sought domestic and international research and other relevant publications related to the integration of PTC with EEW. The literature search also gathered information about I-ETMS (Interoperable Electronic Train Management System), a proprietary system used by rail agencies in California and other states to implement PTC.

Summary of Findings

While we found no published research or other publications related to domestic or international efforts to integrate EEW and PTC, we identified publications that address each topic area individually. These documents provide background information that may be useful to Caltrans as it considers a potential pilot program to integrate PTC and EEW.

Below is a summary of the key resources we identified in three topic areas:

- Positive train control (federal guidance and California experience).
- I-ETMS (Interoperable Electronic Train Management System).
- Earthquake early warning alert systems (domestic and international experience).

Refer to the **Detailed Findings** section of this report for further details of the publications described below and additional citations.

Positive Train Control

Significant federal guidance is available from a compilation of Federal Railroad Administration (FRA) publications produced from January 2015 through July 2018 that describe FRA research on PTC. We provide a link to this compilation and two examples of the publications available. A September 2018 Congressional Research Service report examines PTC policy issues, including interoperability, avoiding barriers to market entry, and PTC requirements within passenger terminals. A sampling of publications describing California's experience with PTC includes a July 2017 report that examines Metrolink's efforts to integrate PTC into its operations and the technological, human, organizational and systematic challenges it faced.

I-ETMS (Interoperable Electronic Train Management System)

We provide a sampling of publications that examine the application of I-ETMS, a proprietary system used by rail agencies in California and other states to implement PTC. An August 2018 FRA press release announcing federal funding awards for PTC implementation includes descriptions of commuter-related PTC deployments underway in other states that will use I-ETMS. In a March 2018 Government Accountability Office (GAO) publication, testimony before the U.S. Senate Committee on Commerce, Science and Transportation highlights challenges with interoperability and offers lessons learned from railway agencies that have implemented I-ETMS.

Two 2015 publications examine technical issues associated with PTC implementation:

- A December 2015 FRA publication examines alternative interoperable train control messaging topologies.
- A September 2015 GAO publication offers some perspective on the complexities of I-ETMS and how they have impacted PTC installations.

Finally, findings from a case study of PTC risk assessment conducted in connection with a 68-mile railway corridor in San Bernardino are presented in a September 2014 FRA report. The authors noted that "[a]s modeled, I-ETMS mitigates all but negligible risk of PTC-preventable accidents with a high degree of confidence."

Earthquake Early Warning Alert Systems

The U.S. experience with EEW appears to be focused on ShakeAlert, the EEW system developed and tested by U.S. Geological Survey (USGS) and a coalition of state and university partners. ShakeAlert pilots and tests are described in a 2018 USGS publication that also presents a technical implementation plan, and in an October 2018 news post that describes a systemwide demonstration of Bay Area Rapid Transit's (BART's) response to a ShakeAlert warning. Further details of ShakeAlert and related systems are available from a web site hosted by Berkeley Seismological Laboratory at the University of California, Berkeley, a partner in ShakeAlert system development.

Other publications highlight EEW system development and research conducted abroad:

- *China*. Researchers examine a new EEW alarm method that reconciles timeliness and stability for use on China's high-speed rail system. The new system issues a P wave warning when the system receives the first seismic wave, which makes the train decelerate. The system then confirms whether the P wave alarm is correct and takes appropriate measures according to the result.

Note: ScienceDirect provides this description of a P wave (see https://www.sciencedirect.com/topics/earth-and-planetary-sciences/p-wave):

> P waves are formed when energy is applied exactly at right angles to a medium. Particle motion under the influence of the wave is then in the direction of propagation of the wave. As a result of the particle motion, the rock particles are alternatively compressed and rarefracted or pulled apart as the waves propagate. P waves are also known as compressional waves, because of the pushing and pulling they do. They are the fastest kind of seismic waves.

- *France*. A system developed for use on France's national state-owned railway system is designed to "automatically slow down or if necessary stop the train a few seconds after detection of an earth tremor liable to deform the tracks, to avoid it reaching the damaged areas at full speed."
- *Japan.* Two publications examine the use of an EEW alert during the March 2011 earthquake that impacted Japan's Tohoku region:
  - An April 2015 Caltrans report offers lessons learned that were gleaned from the experience of East Japan Railway Company (JR East) in the Great East Japan Earthquake of 2011.
  - A 2013 journal article summarizes the configuration of the EEW alert system used during the 2011 Tohoku earthquake, the warning logic adopted for the system, and system performance.

International use of EEW systems is also examined in a 2015 journal article that recommends improvements to the algorithms used for EEW and describes the tests used to validate performance for actual use. A 2011 conference proceeding and 2013 journal article describe wireless sensor networks that can be used to produce accurate and timely reports of earthquakes under geographical and geological prediction limitations and communication constraints.

Gaps in Findings

As previously noted, the literature search conducted for this project did not identify publicly available documents that indicate integration of PTC and EEW is being explored domestically or abroad. The publications included in each of the three topic areas addressed in this report are a sampling of publicly available resources. Additional publications are available should the project panel wish to delve more deeply into a specific topic area.

Next Steps

Moving forward, Caltrans could consider:

- Exploring in greater detail the background information provided in this Preliminary Investigation in connection with PTC, I-ETMS and EEW to identify critical details that can inform a future pilot program to integrate these systems.
- Reviewing the extensive list of FRA publications that address PTC implementation to identify the topic areas of greatest interest to Caltrans.

- Consulting with other states and rail agencies with efforts underway to employ I-ETMS in a PTC implementation to determine if these efforts could inform development of a future pilot program in California. See pages 9 and 10 for a listing of these agencies.
- Contacting BART and other agencies participating in ShakeAlert EEW pilot projects to learn more about test results.

Detailed Findings

Background

Currently, California has three intercity passenger rail lines and five commuter rail systems, and the California High-Speed Rail Authority is constructing a high-speed rail system that will eventually extend from Sacramento to San Diego.

The federal Passenger Rail Investment and Improvement Act of 2008 included a requirement for passenger and major freight railroads to install positive train control (PTC) on most major routes by the end of 2015. A 2010 report published by the U.S. Government Accountability Office (see https://www.gao.gov/new.items/d11133.pdf) described PTC as "a system designed to prevent accidents caused by human factors, including train-to-train collisions and derailments that result from trains exceeding safe speeds. It is also designed to prevent incursions into work zones and movement of trains through switches left in the wrong position." In 2015, Congress extended the deadline for PTC system activation to December 31, 2018. Railroads could also meet the statutory requirements to qualify for an alternative schedule for up to two additional years to complete full implementation.

As California prepares to meet the federal government-mandated installation of a PTC system to improve train safety, Caltrans is also concerned about the potential hazard to rail infrastructure and operations from earthquakes and seismic activity. California is one of the most earthquake-prone states in the nation, and integrating earthquake early warning (EEW) alert systems into PTC has the potential to save lives and protect railroad assets. Caltrans is interested in identifying current efforts to integrate EEW with PTC that could inform a potential pilot project in California that develops and tests an integrated PTC/EEW system.

While a review of publicly available domestic and international literature did not uncover efforts to integrate these systems, the search identified publications that describe the implementation of PTC and EEW systems individually. We also gathered a sampling of publications describing the use of I-ETMS (Interoperable Electronic Train Management System), a proprietary system used by rail agencies in California and other states to implement PTC. The publications that follow are organized into three topic areas:

- Positive train control (federal guidance and California experience).
- I-ETMS (Interoperable Electronic Train Management System).
- Earthquake early warning alert systems (domestic and international experience).

Positive Train Control

The citations below are a sampling of the federal publications that offer guidance on PTC implementation and briefly describe some of the PTC implementation efforts underway in California.

Federal Guidance

Research Publications on Positive Train Control (PTC) January 2015–July 2018, Federal Railroad Administration, undated.
https://www.fra.dot.gov/Elib/Details/L19694
This two-page document provides links to research-related publications on PTC that are available through the Federal Railroad Administration (FRA) web site. The documents cited in *Related Resources* below are examples of the publications appearing on this list.

Related Resources:

> **Positive Train Control Interoperability Test Support: Radio Frequency Desense Testing**, Federal Railroad Administration, July 2018.
> https://www.fra.dot.gov/Elib/Document/18067
> FRA conducted research to evaluate the performance of the Advanced Civil Speed Enforcement System (ACSES) 220 MHz data radios and the Interoperable Train Control (ITC)-compliant 220 MHz data radios when they were in close geographical proximity. Results from the radio frequency (RF) tests "provided information that the industry can use to quantify the effects that dissimilar PTC radios have on one another. As a result, the industry has decided to collaborate on a successful PTC deployment solution of both ACSES and ITC in the same or neighboring geographical locations, such as seen on the NEC [Amtrak commuter line operated in the Northeast]. Two FRA-funded projects were awarded near the completion of this project to further investigate the potential of RF filter or active interference cancelling technologies to mitigate the desense issues for a locomotive equipped with both ITC and ACSES."
>
> **PTC Test Facility Assessment and Laboratory Development: Phase I**, Ryan Sheehan, Thomas Nast, Alan Polivka and Joseph Brosseau, Federal Railroad Administration, April 2018.
> https://www.fra.dot.gov/Elib/Document/17945
> The project's objectives are described on page 2 of the report (page 9 of the PDF):
>
> > The PTC Test Facility Assessment and Laboratory Development project was divided into multiple phases. The following are the objectives of Phase I:
> >
> > 1. Conduct an initial assessment of railroad PTC test cases.
> > 2. Perform a high-level analysis to determine recommendations for developing and executing a plan to implement an industry standard PTC test laboratory.
> > 3. Gather information for the PTC test laboratory that will be needed to develop cost and schedule estimates for Phase II.

The Phase I report describes test methodology, test case management and laboratory architecture; Phase II will develop the test laboratory implementation plan. Future phases are expected to:

1. Implement test capabilities and/or facilities identified in Phase II to support short line and commuter PTC testing needs.
2. Expand test laboratory facilities' scope and scale identified in Phase II to support ongoing industry PTC test needs.

Positive Train Control (PTC): Overview and Policy Issues, Congressional Research Service, September 2018.
https://fas.org/sgp/crs/misc/R42637.pdf
This report prepared for members and committees of Congress addresses a range of issues related to PTC, including rail safety and PTC; implementation issues domestically and abroad; costs and benefits, including safety benefits; and policy issues such as interoperability, avoiding barriers to market entry, and PTC requirements within passenger terminals.

"Positive Train Control: Engineering Basics and Lessons Learned," Devin Rouse, Office of Railroad Safety, Federal Railroad Administration, *FRA Program Delivery Conference*, October 2015.
https://www.fra.dot.gov/Elib/Document/15386
This presentation provides an introduction to PTC and discusses engineering considerations and lessons learned. The presentation closes with a brief listing of guidance documents and contacts to obtain technical assistance.

California Experience

Technical and Safety Evaluation of the Southern California Regional Rail Authority Positive Train Control Deployment Project: Challenges and Lessons Learned, Greg Placencia, John Franklin and James E. Moore II, Federal Transit Administration, July 2017.
https://www.transit.dot.gov/sites/fta.dot.gov/files/docs/research-innovation/64636/ftareportno0112.pdf
This report describes the efforts of Southern California Regional Rail Authority (SCRRA, or Metrolink) to integrate PTC into its operations, and the technological, human, organizational and systematic challenges it faced when implementing the new technology.

The report describes and applies the concept of a high reliability organization (HRO), which "was developed to help organizations operating in high-hazard environments maintain low risks while concurrently managing tightly-scheduled operations using five basic organizational principles:

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

Page 24 of the report (page 32 of the PDF) illustrates application of these principles using case studies of previous crashes.

"Stepped-Up Safety: California Rail Agencies on a Roll With Adoption of Positive Train Control," Stephanie Jordan, *Transit California*, California Transit Association, April 2017.
https://caltransit.org/news-publications/publications/transit-california/transit-california-archives/2017-editions/april/stepped-up-safety/
This article summarizes how California rail properties are progressing toward meeting a 2018 PTC implementation deadline.

High-Speed Rail Safety Program, California High-Speed Rail Authority, April 2016.
https://www.hsr.ca.gov/docs/newsroom/fact%20sheets/cahsr_safety_2016.pdf
This document describes California High-Speed Rail Authority's (CHSRA's) support of PTC statewide and CHSRA's adoption of an EEW system designed to immediately cut off power to trains in operation at the time of an earthquake. The possible integration of EEW with PTC is not addressed.

I-ETMS (Interoperable Electronic Train Management System)

I-ETMS is a proprietary system used by rail agencies in California and other states to implement PTC. The vendor's web site provides high-level information about this system:

> **I-ETMS (Interoperable Electronic Train Management System)**, Wabtec Corporation, 2018.
> https://www.wabtec.com/markets/freight-segment-ptc-signaling-wayside-market
> *From the web site:* A leader in the development and deployment of on-board electronic train-control systems, Wabtec's safety-overlay system, I-ETMS (Interoperable Electronic Train Management System), integrates new technology with existing train control and operating systems to enhance train operation safety. I-ETMS helps prevent track authority violations, speed limit violations and unauthorized entry into work zones to help reduce the potential for train accidents. I-ETMS also queries wayside devices for broken rails, proper switch alignment and signal aspects. The information is combined and analyzed in real time to provide a "safety net" for improved train operation.

The publications cited below are a sampling of the resources that provide general information about I-ETMS and its application in two categories:

- National guidance.
- Related resources.

National Guidance

"FRA Awards More Than $200 Million for PTC Implementation," Press Release, Federal Railroad Administration, August 2018.
https://railroads.dot.gov/newsroom/fra-awards-more-200-million-ptc-implementation
This web site describes projects in 15 states that were awarded FRA funding to assist with PTC deployment. In addition to PTC deployments in California, this web site describes other states' commuter-related PTC deployments that will use I-ETMS, including:

- *Florida Department of Transportation*. Completes installation of I-ETMS, with testing and documentation to support PTC System Certification, on the 61.3-mile Central Florida Rail Corridor from DeLand to Poinciana, Florida.

- *Chicago Rail Link (CRL)*. Includes onboard computer equipment and communication systems, locomotive radio licenses, messaging licenses, and a back-office service messaging systems management license, along with PTC system testing and training to support the five CRL and Illinois Railway locomotives operating on the Metra commuter rail system in and around Chicago, as Metra and Burlington Northern Santa Fe (BNSF) Railway activate I-ETMS PTC systems.
- *Chicago South Shore & South Bend Railroad (CSS)*. Includes I-ETMS installation, testing and training as well as interoperability between CSS and the host railroad, Northern Indiana Commuter Transportation District, along a route from Chicago to South Bend, Indiana.
- *Northern Indiana Commuter Transportation District (NICTD)*. Completes the design, implementation, training and support of NICTD's I-ETMS PTC system for the wayside, onboard, locomotive, back office and communications segments to enhance the safety of commuter rail passenger transportation between South Bend, Indiana, and Chicago.
- *Dallas Area Rapid Transit (DART)*. Supports implementing a PTC back-office system, I-ETMS systems integration and testing with multiple freight and passenger railroads, interoperability testing and training for the Trinity Railway Express and TEXRail commuter railroads in the Dallas-Fort Worth urban area.

Positive Train Control: Many Commuter Railroads Still Have Significant Additional Implementation Work and Opportunities Exist to Provide Federal Assistance, Testimony Before the Committee on Commerce, Science and Transportation, U.S. Senate, United States Government Accountability Office, March 2018.
https://www.gao.gov/assets/700/690376.pdf
A footnote to this testimony to Congress indicates that "[f]ifteen commuter railroads are implementing I-ETMS—the main system used by freight railroads. Six commuter railroads—located throughout the United States—are implementing E-ATC [Enhanced Automated Train Control] and 5—on the Northeast Corridor between Boston and Washington, D.C.—are implementing forms of the Advanced Civil Speed Enforcement System. Two of the remaining commuter railroads are implementing different types of PTC systems, and one has yet to determine what PTC system it will implement."

Another footnote indicates that "[t]he 7 Class I railroads created a consortium—PTC 220 LLC—to purchase radio frequency spectrum licenses that would address their needs, and in some cases, the consortium can lease radio frequency spectrum to non-Class I railroads for a fee. Most commuter railroads installing the I-ETMS system have opted to lease spectrum from PTC 220 LLC."

The report also highlights challenges with interoperability and host and tenant coordination (from page 17 of the document, page 19 of the PDF):

> As noted above, PTC is being implemented by different types of railroads using different systems, and achieving interoperability among PTC systems can complicate implementation. For example, Northeast Corridor railroads that are implementing versions of the Advanced Civil Speed Enforcement System need interoperability with freight railroads using I-ETMS. Even railroads that are installing the same PTC system have to take significant steps to ensure that systems will communicate and interoperate properly. In one case, a railroad told us that it is equipping its locomotives with equipment for multiple PTC systems to ensure that it can operate on various host railroads' tracks.

> Some commuter railroads that only operate as tenants on other railroads' tracks may be able to complete some PTC implementation work more quickly, as these railroads may benefit from work the host railroads already completed as they coordinate to implement PTC. For example, representatives from one commuter railroad we spoke with said they have to acquire and install PTC equipment on their locomotives but rely on the host railroads to install the remainder of the necessary PTC infrastructure. These tenant-only commuter railroads, however, have to coordinate field testing and RSD [revenue service demonstration] with the host railroads.

Lessons learned begin on page 19 of the document (page 21 of the PDF):

> As railroads continue to progress with their projects and the industry becomes more experienced with PTC, railroads could benefit from lessons learned. For example, representatives from one railroad that is implementing I-ETMS, the system all large Class I freight railroads are implementing, told us that they anticipate being able to capitalize on lessons learned from freight railroads that have operated in RSD. By leveraging the freight railroads' experiences, one commuter railroad hopes to address issues before testing, rather than during, and therefore move more quickly through the testing process. If commuter railroads are able to apply lessons learned from other railroads' testing processes, then they may be able to accelerate their implementation efforts. Railroads may also accelerate implementation schedules as they become more adept at the overall testing process, which involves submitting test documents to FRA and scheduling multiple tests. This could potentially shorten the average time it takes a railroad to complete one or more of the key milestones analyzed. The two commuter railroads that have been conditionally certified told us they have met with other commuter railroads informally and have shared their project experiences as a way to facilitate information sharing.

Positive Train Control Interoperability and Networking Research, Federal Railroad Administration, December 2015.
https://www.fra.dot.gov/Elib/Document/15549
This project examined alternative interoperable train control (ITC) messaging topologies "that would extend ITC messaging beyond the shared network environment for short line and commuter access across a simulated Multi-Protocol Label Switching (MPLS) link to a Class I back office server." Researchers also examined the distribution of virtual machine technologies across more than one physical location, and introduction of a reliable message router capability to support shared network scalability. Core findings described in the executive summary include:

- ITC messaging and ITC systems management functions can be hosted in a shared network environment.
- Initialization can be conducted across a shared network environment for a simulated short line or commuter locomotive to a simulated short line, commuter, or Class I back office.
- An ITC PTC shared network can directly support the integration of technology and methodology in the development of ITC PTC message interoperability between the short line and commuter rails with the Class I railroads.
- The short line and commuter railroads have expressed a great deal of interest in the shared network concept. The PTC component and process allocations can help railroads plan for PTC deployment.

Positive Train Control: Additional Oversight Needed as Most Railroads Do Not Expect to Meet 2015 Implementation Deadline, Report to Congressional Requesters, United States Government Accountability Office, September 2015.
https://www.gao.gov/assets/680/672717.pdf
The report's background describes the two primary PTC systems being implemented by railroads:

> There are two primary PTC systems being implemented by railroads: Interoperable Electronic Train Management System (I-ETMS) and Advanced Civil Speed Enforcement System (ACSES). All Class I railroads in the United States plan to implement I-ETMS, which will account for most of the approximately 68,000 route miles that are required to be equipped with PTC. (See fig. 1). Amtrak is implementing ACSES on the Northeast Corridor that runs between Boston and Washington, D.C. Although ACSES and I-ETMS are functionally similar, the technologies they use differ. For example, to determine train location, ACSES relies on track-embedded transponders while I-ETMS uses Global Positioning System information. Since most commuter and Class II/III railroads run over tracks owned by freight railroads or Amtrak, they are largely implementing the same systems developed by the freight railroads or Amtrak.

Page 13 of the report (page 17 of the PDF) provides some perspective on the challenges identified by railroad representatives when developing system components and installing PTC:

> I-ETMS Complexities: As discussed in our prior report, selected railroads and AAR identified challenges with developing the I-ETMS's back office server as one of the critical factors railroads anticipated would prevent them from meeting the PTC deadline. At that time, they anticipated securing a final version of the back-office server in 2014. However, this system is still in final testing and, according to AAR, is expected to be finalized in late 2015. Of the railroads we interviewed, 21 of 29 stated that developing PTC components, including back office systems, is one challenge that is affecting or may affect their PTC implementation. Among the railroads that expect to finish installing PTC on their tracks and locomotives by the end of 2015, 4 of the 5 said they are not installing I-ETMS. Representatives from one of these railroads specifically mentioned not installing I-ETMS as one reason that they anticipate being able to meet the deadline. The one railroad that is installing I-ETMS noted that it had to change vendors after difficulties with obtaining a back-office server delayed its implementation. In addition, representatives of industry associations and Class II/III railroads told us that while they previously thought they could use their host railroads' back office systems, there have been indications that in some cases, they may need to obtain their own back office systems. This is a decision being made between host and tenant railroads. Representatives of one Class II/III railroad indicated to us that they will use their Class I host railroad's back office system, but others indicated they may have to develop their own; this may be costly and these railroads may lack in-house resources to maintain such systems. Representatives also told us that they are exploring the use of a virtual back office that would be shared among several railroads and managed by a third party.

BNSF San Bernardino Case Study: Positive Train Control Risk Assessment, Daniel Brod and Boaz Leslau, Federal Railroad Administration, September 2014.
https://www.fra.dot.gov/Elib/Document/14096
This case study used a generalized train movement simulator to evaluate the risk associated with the planned implementation of the I-ETMS PTC system on the 68-mile BNSF San Bernardino corridor, which handles more than 100 freight and passenger trains daily, including trains from BNSF, Union Pacific, Amtrak and Metrolink. As the authors note, the "corridor is regarded as one of the most heavily trafficked and operationally complex in the United States."

As the abstract indicates, “[a]s modeled, I-ETMS mitigates all but negligible risk of PTC-preventable accidents with a high degree of confidence. A sensitivity analysis confirms these results. Changes to operating assumptions that could indicate greater risk in the Base Case actually show small variance in total risk. However, there is greater variance in the mix of accidents by accident type.”

Related Resources

“Positive Train Control Security: An Intrusion-Detection System to Provide Cyber-Situational Awareness,” Satish Kolli, Joshua Lilly and Duminda Wijesekera, *IEEE Vehicular Technology Magazine*, Vol. 13, Issue 3, September 2018.
Citation at https://ieeexplore.ieee.org/document/8411331
From the abstract: American railroads plan to complete implementation of their positive train control (PTC) systems by 2020, with the primary safety objectives of avoiding intertrain collisions/train derailments and ensuring railroad worker safety. Under published Interoperable Electronic Train Management System (I-ETMS) specifications, the onboard unit (OBU) communicates with two networks: 1) the signaling network that conveys track warrants to occupy blocks and 2) the wayside interface unit (WIU) network, a sensor network situated on tracks to gather navigational information. These include the status of the rail infrastructure (such as switches) and any operational hazards that may affect the intended train path.

Positive Train Control, The Joint Council on Transit Wireless Communications, May 2012.
https://ecfsapi.fcc.gov/file/7520923910.pdf
This white paper reviews the “two major technical architectures [that] have emerged” to address PTC:

- Advanced Civil Speed Enforcement System, implemented on Amtrak’s Northeast Corridor.
- I-ETMS, implemented by California’s Metrolink and other rail agencies.

In addition to briefly examining these systems, the white paper considers technology challenges and the PTC “vendor ecosystem.”

Earthquake Early Warning Alert Systems

Experience with EEW in the United States is focused largely on ShakeAlert, the EEW system developed and tested by U.S. Geological Survey and a coalition of state and university partners. The international experience is described in publications that highlight EEW system development and research conducted in China, France and Japan.

U.S. Experience

Earthquake Early Warning, Earthquake Hazards Program, U.S. Geological Survey, undated.
https://earthquake.usgs.gov/research/earlywarning/
This web site provides an overview, background, current status, next steps and news on EEW systems.

Revised Technical Implementation Plan for the ShakeAlert System—An Earthquake Early Warning System for the West Coast of the United States, Douglas D. Given, Richard M. Allen, Annemarie S. Baltay, Paul Bodin, Elizabeth S. Cochran, Kenneth Creager, Lind S. Gee, Egill Hauksson, Thomas H. Heaton, Margaret Hellweg, Jessica R. Murray, Valerie I. Thomas, Douglas Toomey and Thomas S. Yelin, U.S. Geological Survey, 2018.
http://seismo.berkeley.edu/research/eew_docs/ShakeAlert-TechnicalImplementationPlan-USGS-OFR-2018-1155-2018.pdf
This examination of the status of ShakeAlert implementation includes a discussion of pilots, including the following from page 27 of the report (page 37 of the PDF):

> Many pilots are operational now. For example, the Bay Area Rapid Transit (BART) system was an early adopter and began to use ShakeAlert in August 2012 (McPartland, 2013). BART can reduce train speeds from 80 to 25 miles per hour in about 18 seconds, making derailment during earthquake shaking less likely. The Los Angeles light rail system, LA Metro, is following their lead. Appendix 3 [see page 40 of the report, page 50 of the PDF] lists current pilot organizations and projects. The list is growing rapidly as ShakeAlert becomes better known and alerts are made available.

"BART Tests Earthquake Early Warning System as ShakeAlert Becomes Available to All Bay Area Organizations," Robert Sanders, *Berkeley News*, University of California, Berkeley, October 5, 2018.
https://news.berkeley.edu/2018/10/05/bart-tests-earthquake-early-warning-system-as-shakealert-becomes-available-to-all-bay-area-organizations/
From the news post:

> **WHAT**: A systemwide demonstration of BART's response to an earthquake early-warning alert from the ShakeAlert system, which is now being offered to all Bay Area businesses, utilities and app developers.
>
> Following the test, federal and state legislators, BART officials and UC Berkeley seismologists will hold a press conference to announce the newest version of ShakeAlert, emphasize its key role in protecting public safety and infrastructure and make a case for continued federal and state funding to expand the system throughout the earthquake-prone West Coast.

> **WHEN**: Between 11 and 11:15 a.m. Monday, Oct. 8, trains will slow to 27 miles per hour and stations and trains will broadcast an alert to passengers in a test of BART's response to a real ShakeAlert warning.

ShakeAlert: An Earthquake Early Warning System for the West Coast of the United States, U.S. Geological Survey Earthquake Early Warning, 2016.
https://www.shakealert.org/
From the web site: ShakeAlert is an earthquake early warning (EEW) system that detects significant earthquakes so quickly that alerts can reach many people before shaking arrives.

The U.S. Geological Survey (USGS) along with a coalition of State and university partners is developing and testing the ShakeAlert System for the West Coast of the United States. Before general public alerting can begin long-term operational funding must be secured and the speed and reach of mass alerting technologies must be tested and improved. Many partnerships to test ShakeAlert in authentic environments such as utilities, hospitals and in schools are active today and more are being developed. The USGS has set the goal of expanding these applications in 2018 and beginning public notifications as soon as mass notification pathways can support them.

Earthquake Early Warning at the Berkeley Seismology Lab, Berkeley Seismological Laboratory, University of California, Berkeley, undated.
http://seismo.berkeley.edu/research/eew_basics.html
From the web site:

> ShakeAlert is the name of the public earthquake early warning system now being implemented in California, Oregon and Washington. The ElarmS algorithm developed by the UC Berkeley Seismological Laboratory is one of the core ShakeAlert algorithms and is typically the source of the first alert message.

Links on the web site offer access to additional information about other EEW-related projects, including:

- ElarmS, a "robust earthquake early warning system that has successfully alerted on hundreds of events throughout California since it was developed in 2007." The lab recently began expanding ElarmS coverage into the Pacific Northwest (Washington and Oregon), and versions of ElarmS are being tested in Israel, Turkey and Chile.
- GlarmS, an EEW algorithm for big quakes (magnitude > 7) that builds on the alert provided by ElarmS using geodetic data, and tracks the geographic extent of the fault rupture. The system is currently being tested in real time along the U.S. West Coast for inclusion in ShakeAlert.

International Experience

"A Combined Method for High-Speed Rail Seismic Monitoring and Early Warning," Zhigao Chen and Jun Huang, *Geodesy and Geodynamics*, Vol. 8, No. 5, pages 356-360, September 2017.
https://www.sciencedirect.com/science/article/pii/S1674984717300587
From the abstract: The ground motion characteristics include the strength, frequency spectrum and duration time. In China, the PGA (peak ground acceleration) is commonly used in determination of whether an earthquake warning is necessary when the high-speed train is on the rail. This method has not given an earthquake early warning time, and it only considers the

strength factor of an earthquake, so the system may release an alarm for the near and small earthquakes which are no[t] destructive. The new alarm method reconciles the timeliness and stability. It issues a P wave warning when the system receives seismic wave first, which will make the train to decelerate. Then, the system will confirm whether the P wave alarm is correct using the joint alarm result of CAV (cumulative absolute velocity) and PGA, and then take measures according to the result. The new method eliminates the interference from the near and small earthquakes, as well as the large and far earthquakes, and ensures the safety of the train when it is subjected to earthquakes. In this paper, we use seismic data to simulate the combined alarm of CAV and PGA, and then obtain the cumulative time of CAV and the time interval between CAV and PGA. Finally, we compare the new method with the double-station, earthquake monitoring alarm method which is currently used on China's high-speed rail, and find the new alarm method is better in the aspect of alarm timeliness.

Note: ScienceDirect provides this description of a P wave (see https://www.sciencedirect.com/topics/earth-and-planetary-sciences/p-wave):

> P waves are formed when energy is applied exactly at right angles to a medium. Particle motion under the influence of the wave is then in the direction of propagation of the wave. As a result of the particle motion, the rock particles are alternatively compressed and rarefracted or pulled apart as the waves propagate. P waves are also known as compressional waves, because of the pushing and pulling they do. They are the fastest kind of seismic waves.

Case Study: Earthquake Early Warning TGV High-Speed Railway Marseille, France, GeoSIG Ltd., 2016.
https://www.geosig.com/files/CaseStudy_TGV_HighSpeedRailway_France.pdf
From the publication: The aim of the system is to automatically slow down or if necessary stop the train a few seconds after detection of an earth tremor liable to deform the tracks, to avoid it reaching the damaged areas at full speed.

Configuration of the system designed by the CEA [Commissariat à l'Energie Atomique, or Central Commission of Nuclear Energy] and DASE [Département Analyse, Surveillance, Environnement, or Environmental Assessment and Monitoring Department] consists of 24 measurement stations, set 10 km apart, which are installed along the tracks in the seismic area between Valence, Marseille and Nîmes. In the event of ground motion above certain thresholds, a central sign posting unit in Marseille—collecting and processing all station data—sends an order to slow down or stop trains to the SNCF [Société Nationale des Chemins de Fer, France’s national state-owned railway company] system, which centralizes all safety alarms for the line.

At the same time, a separate automatic decision support system, located in Bruyères-le-Châtel, integrates data from 14 stations of the CEA’s national seismic monitoring network, to confirm (or not) the presence of an earthquake within a 10 minute interval. This allows the SNCF to take an informed decision (resume normal operation of the line or inspect the tracks).

The devices are connected via the SNCF’s fiber optic networks and dedicated lines.

Great East Japan Earthquake, JR East Mitigation Successes, and Lessons for California High-Speed Rail, Frances L. Edwards, Daniel C. Goodrich, Margaret Hellweg, Jennifer A. Strauss, Martin Eskijian and Omar Jaradat, California Department of Transportation and Office of the Assistant Secretary for Research and Technology, April 2015.
http://transweb.sjsu.edu/sites/default/files/1225-great-east-japan-earthquake-lessons-for-California-HSR.pdf
This report's conclusions, which begin on page 46, offer lessons learned gleaned from the experience of East Japan Railway Company (JR East) in the 2011 Great East Japan Earthquake, which impacted Japan's Tohoku region. The best practices highlighted below can inform development of an EEW system for CHSRA:

- EEW prevents derailments.
- Automatic electricity shut-off and brake application are critical to success—seconds count.
- Location of sensors in relation to the fault determines the length of the warning period.
- Direct delivery of warnings to the public through mobile devices and computer screens enhances the value of EEW beyond the benefits of media-based notices.
- EEW can be used for immediate protective measures as well as for understanding the event to manage the response most effectively.
- Faster computers and more effective algorithms enhance the speed and accuracy of the EEW system.
- EEW's value depends on the resiliency of the built environment.
- Periodic re-evaluation of infrastructure resilience is critical.
- Timely retrofit of infrastructure elements enhances the likelihood of system resilience.
- Infrastructure owners must learn from each new seismic event and upgrade, retrofit and replace critical connectors and supports to enhance resiliency.
- Trained staff are essential to an appropriate response to the EEW alarm.
- Exercises with staff and public maintain awareness of the appropriate response to EEW alarms.

"Improved Algorithms of Seismic Parameters Estimation and Noise Discrimination in Earthquake Early Warning," Naoyasu Iwata, Shunroku Yamamoto, Masahiro Korenaga and Shunta Noda, *Quarterly Report of Railway Technical Research Institute*, Vol. 56, No. 4, pages 291-298, 2015.
Citation at http://dx.doi.org/10.2219/rtriqr.56.4_291
From the abstract: Improvements were made to the algorithms used for earthquake early warning, followed by tests to validate their performance for actual use. The upgraded algorithms are capable of producing more accurate and timely estimations of seismic parameters, compared with current algorithms. This new technique contributes to raising train operating safety during earthquakes. Another enhanced algorithm was devised for seismographs installed along railway lines, which makes them capable of discriminating between earthquake motion and train-induced vibrations. These improvements to the seismographs are expected to increase the reliability of earthquake early warning.

"Earthquake Early Warning System for Railways and Its Performance," Shunroku Yamamoto and Masahiko Tomori, *Journal of JSCE*, Vol. 1, pages 322-328, 2013.
https://www.jstage.jst.go.jp/article/journalofjsce/1/1/1_322/_pdf
From the abstract: During the 2011 off the Pacific coast of Tohoku Earthquake, the earthquake early warning system operated by East Japan Railway Company controlled the Shinkansen trains through information from its seismic stations before large shakings hit the line. By analyzing the event history of the system recorded in its monitoring PCs [personal computers], it was confirmed that the system first detected the seismic motion at 14:46:38.9 (JST) based on the data of the Kinkazan seismic station located closest to the epicenter, and issued the first control signal to trains between Shiroishi-Zaoh station and Kitakami station of the Tohoku Shinkansen line at 14:47:02.9 through the excess of acceleration threshold of the Kinkazan seismic station. The signal was issued 12-22 seconds earlier than the time SI [spectrum intensity] value exceeding 18 cm/s along the line, which is the required value to stop trains based on company rules. After issuing the first control signal, other seismic stations began issuing signals through the excess of acceleration threshold almost sequentially according to certain delays caused by wave propagation from the hypocenter. Eventually, 27 trains (19 of them were running) along the line were safely controlled. In this paper, after summarizing the configuration of the earthquake early warning system of East Japan Railway Company and the warning logics adopted for the system, the system performance during the 2011 off the Pacific coast of Tohoku Earthquake is evaluated and discussed in detail.

"Minimum Cost Deployment in Earthquake Early Warning System for High-Speed Railways," Yi Yuan, Dan Wang and Yi-Qing Ni, *2013 IEEE International Conference on Intelligent Rail Transportation Proceedings*, pages 227-232, 2013.
Citation at https://ieeexplore.ieee.org/document/6696298
From the abstract: In recent years, earthquake early warning systems (EEW) attract great attention from public because losses of lives and properties can be greatly reduced with earthquake alarm it offers. However, conventional EEW system cannot offer satisfactory alarms for high-speed railway systems. Therefore, it is necessary to develop an EEW for high-speed railways (HR-EEW). One of the key issues in designing an HR-EEW system is how to offer timely alarms to trains under certain constrain[t]s, such as budget limitation and geological restriction. We propose HR-EEW systems based on wireless sensor networks (WSNs). In this paper, we take a close look at deploying wireless sensor nodes in HR-EEW systems. We target at solving the minimum cost deployment problem while guaranteeing that any earthquake in a seismic district can be timely reported by k sensors. We carefully investigate this problem and derive a critical condition for a deployment to satisfy a predefined performance requirement. Then, we present novel algorithms to solve the problem. Finally, we evaluate our methodology under real data and synthetic data.

"Wireless Sensor Networks for Earthquake Early Warning Systems of Railway Lines," Dan Wang and Yiqing Ni, *Proceedings of the 1st International Workshop on High-Speed and Intercity Railways,* pages 417-426, July 2011.
Citation at https://link.springer.com/chapter/10.1007/978-3-642-27963-8_38
From the abstract: There are many earthquake early warning systems. The key of the EEW is an *accurate* and *timely* report of earthquake warning under such constraints as geographical and geological prediction limitation, communication constraints, fault tolerance; to name but a few.

Wireless sensor network (WSN) is used in many domains due to its advantage in cost, simple maintenance, robustness, etc. There are calls to use WSN for EEW in recent years. In this paper, we first present a modular designed WSN framework for EEW. In this framework, we study two bottlenecks of applying WSN to EEW. First, we study the locations that the sensors should be placed (or the sensor density), so as to achieve a timely warning report and system efficiency. We observe that wireless communication is faster than the destructive S-wave of the earthquake. Therefore, a trade-off can be made so that the number of the sensors to be deployed or maintained can be significantly reduced. Intrinsically, the faster P-wave of the earthquake should first hit at least one sensor which can gather, compute and transmit this information to the damage prone point, before the S-wave arrives. Second, we study a deadline driven strategy for WSN to reduce false alarms. In this case, the WSN of EEW and the WSN of the railway line health monitoring system will work together. Since the sensors of the railway line health monitoring system of the railway lines are densely deployed, there will be a great number of reports generated. An early aggregation of the information is needed to localize and evaluate the earthquake range and impact. False alarms should be filtered out.

These problems are intrinsic and cannot be improved by engineering advances. A joint foundational understanding of the communication limitation, complexity reduction of the computing systems, and earthquake knowledge is required. We believe that this work can serve as a first step before the development of a practical EEW system.