U.S. Department
of Transportation

**Federal Railroad
Administration**

North American Joint Positive Train Control Project

Office of Research and
Development
Washington, D.C. 20590

DOT/FRA/ORD-09/04

April 2009

REPORT DOCUMENTATION PAGE		**Form approved** **OMB No. 0704-0188**

1. AGENCY USE ONLY *(Leave blank)*	**2. REPORT DATE** April 1, 2009	**3. REPORT TYPE AND DATES COVERED**

4. TITLE AND SUBTITLE
North American Joint
Positive Train Control Project

5. FUNDING NUMBERS

6. AUTHOR(S)
Alan Polivka, Bill Moore Ede, and Joe Drapa

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Transportation Technology Center, Inc.
P. O. Box 11130
Pueblo, CO 81001

Railroad Research Foundation
50 F Street NW, Suite 5200
Washington, DC 20001

8. PERFORMING ORGANIZATION REPORT NUMBERS

9. SPONSORING/MONITORING AGENGY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Research and Development
1200 New Jersey Avenue SE, Mail Stop 20
West Building, 3rd Floor
Washington, DC 20590

10. SPONSORING/MONITORING AGENCY REPORT NUMBER
DOT/FRA/ORD-09/04

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available through National Technical Information Service, Springfield, VA 22161.

12b. DISTRIBUTION CODE

13. ABSTRACT

PTC offers the promise of significant potential benefits in railroad safety, capacity, and efficiency. However, PTC reveals new and much more complex design issues than those encountered with conventional train control systems. This is largely because a PTC system comprises a large, distributed, real-time communications, control, and mobile computing network that embodies and enforces many of the railroad operating rules.

This report summarizes key issues encountered in developing the vital NAJPTC system along with solutions, rationale, and results. The unique experiences gained from this project have benefited other PTC projects and have led to the inception of subsequent projects to further address issues identified.

14. SUBJECT TERMS
Train control, communications-based train control, CBTC, positive train control, PTC, railroad safety, moving block

15. NUMBER OF PAGES
77

16. PRICE CODE

17. SECURITY CLASSIFICATION	**18. SECURITY CLASSIFICATION OF THIS PAGE**	**19. SECURITY CLASSIFICATION OF ABSTRACT**	**20. LIMITATION OF ABSTRACT**
UNCLASSIFIED	UNCLASSIFIED	UNCLASSIFIED	SAR

NSN 7540-01-280-5500

Standard Form 298 (Rec. 2-89)
Prescribed by ANSI/NISO Std.
239.18
298-102

METRIC CONVERSION FACTORS

Approximate Conversions to Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
in	inches	*2.50	centimeters	cm
ft	feet	30.00	centimeters	cm
yd	yards	0.90	meters	m
mi	miles	1.60	kilometers	km

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
in^2	square inches	6.50	square centimeters	cm^2
ft^2	square feet	0.09	square meters	m^2
yd^2	square yards	0.80	square meters	m^2
mi^2	square miles	2.60	square kilometers	km^2
	acres	0.40	hectares	ha

MASS (weight)

Symbol	When You Know	Multiply by	To Find	Symbol
oz	ounces	28.00	grams	g
lb	pounds	0.45	kilograms	kg
	short tons (2000 lb)	0.90	tonnes	t

VOLUME

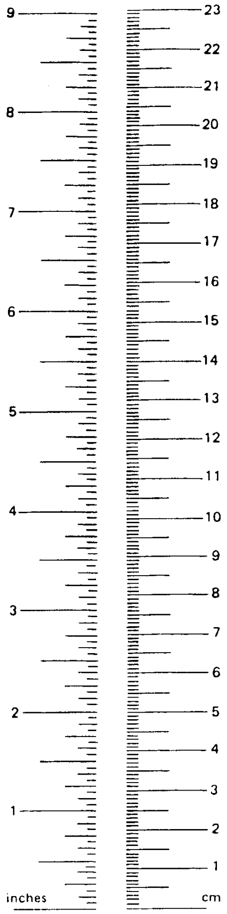
Symbol	When You Know	Multiply by	To Find	Symbol
tsp	teaspoons	5.00	milliliters	ml
Tbsp	tablespoons	15.00	milliliters	ml
fl oz	fluid ounces	30.00	milliliters	ml
c	cups	0.24	liters	l
pt	pints	0.47	liters	l
qt	quarts	0.95	liters	l
gal	gallons	3.80	liters	l
ft^3	cubic feet	0.03	cubic meters	m^3
yd^3	cubic yards	0.76	cubic meters	m^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

---

* 1 in. = 2.54 cm (exactly)



Approximate Conversions from Metric Measures

LENGTH

Symbol	When You Know	Multiply by	To Find	Symbol
mm	millimeters	0.04	inches	in
cm	centimeters	0.40	inches	in
m	meters	3.30	feet	ft
m	meters	1.10	yards	yd
km	kilometers	0.60	miles	mi

AREA

Symbol	When You Know	Multiply by	To Find	Symbol
cm^2	square centim.	0.16	square inches	in^2
m^2	square meters	1.20	square yards	yd^2
km^2	square kilom.	0.40	square miles	mi^2
ha	hectares (10,000 m^2)	2.50	acres	

MASS (weight)

Symbol	When You Know	Multiply by	To Find	Symbol
g	grams	0.035	ounces	oz
kg	kilograms	2.2	pounds	lb
t	tonnes (1000 kg)	1.1	short tons	

VOLUME

Symbol	When You Know	Multiply by	To Find	Symbol
ml	milliliters	0.03	fluid ounces	fl oz
l	liters	2.10	pints	pt
l	liters	1.06	quarts	qt
l	liters	0.26	gallons	gal
m^3	cubic meters	36.00	cubic feet	ft^3
m^3	cubic meters	1.30	cubic yards	yd^3

TEMPERATURE (exact)

Symbol	When You Know	Multiply by	To Find	Symbol
°C	Celsius* temperature	9/5 (then add 32	Fahrenheit temperature	°F

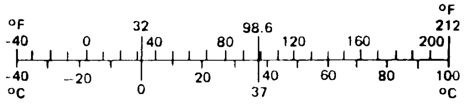


Table of Contents

List of Figures

Acknowledgements

Transportation Technology Center, Inc. (TTCI), a wholly owned subsidiary of the Association of American Railroads (AAR), managed the North American Joint Positive Train Control (NAJPTC) project under contract to the Railroad Research Foundation (RRF). RRF received funding for the project from the Federal Railroad Administration (FRA) under Cooperative Agreement No. DTFR53-03-H-00015. Additional funding was received from AAR and IDOT. The system engineering effort was led by ARINC and included team members CANAC, Battelle, and Parson Transportation Group. The PTC System Developer/Integrator team was led by Lockheed Martin, and included Wabtec, Union Switch and Signal, Parsons-Brinckerhoff, and the University of Virginia. The NAJPTC management committee included representatives from the Union Pacific Railroad (UP), CSX Transportation, Norfolk Southern (NS), BNSF Railway, Canadian National Railway, Canadian Pacific Railway, and Amtrak, and the AAR, FRA, IDOT, Volpe Center, ARINC, Battelle, Lockheed Martin, Wabtec, and TTCI. Stakeholders included representatives from the UP, NS, Amtrak, the AAR, FRA, IDOT, Lockheed Martin, and TTCI.

Executive Summary

The North American Joint Positive Train Control (NAJPTC) project (a.k.a. "Illinois Department of Transportation Positive Train Control (IDOT PTC)" project) was an ambitious multiyear project to develop, test, and demonstrate a vital, interoperable, and cost-effective communication-based train control (CBTC) system that could improve safety and provide operational benefits as compared with conventional systems. The Federal Railroad Administration (FRA), Association of American Railroads (AAR), and IDOT jointly funded the project, and Transportation Technology Center, Inc. (TTCI), a wholly owned subsidiary of the AAR, managed the project.

The NAJPTC system was developed and tested on a 120-mile corridor of the Union Pacific (UP) railroad in Illinois that hosts both freight trains and Amtrak passenger trains. In order to demonstrate overlay and standalone (moving block) methods of operation, the 120 miles of PTC territory was divided into two categories of roughly 60 miles each: "PTC Integrated Territory" and "PTC Standalone Territory." PTC Standalone Territory was to demonstrate the capacity improvements achievable with moving block operation. Trains on PTC Integrated Territory were constrained by conventional fixed signals, so it would not show capacity improvements but was intended to demonstrate efficient handling of nonequipped trains mixed with PTC-equipped trains.

The NAJPTC project addressed the design challenges faced by PTC systems in general and provided valuable lessons learned. Through its design, development, and testing, the NAJPTC system has also aided other PTC projects in a number of ways as described in this report. Subsequent projects have been started that leverage off the NAJPTC project or that address issues encountered on the NAJPTC project requiring further development.

This report presents the objectives, approach, results, benefits, and lessons learned from the NAJPTC project.

Goals and Objectives

PTC is a form of communication-based train control (CBTC). To satisfy the three basic safety characteristics specified by the FRA's Railroad Safety Advisory Committee's PTC Working Group, a PTC system must:

- Prevent train-to-train collisions,
- Enforce speed restrictions and temporary slow orders, and
- Provide protection for workers and their equipment operating under specific authorities.

PTC functions are modular to allow tailored implementation for each railroad or territory. Functionality negotiation capabilities permit trains to automatically adjust to the specifics of each deployment infrastructure. This, along with an open architecture, facilitates interoperability (operating one railroad's locomotive on another railroad's track under

PTC) and migration (supporting different levels of functionality at various stages of evolutionary implementation).

In addition to the safety objectives listed, the complex NAJPTC system would enable increasing passenger train speed to 110 mph. In Standalone Territory, it would also have the potential to increase railroad capacity (reduce excess headway as compared with fixed block signaling) by means of its moving-block architecture. In Integrated Territory, however, it would operate in conjunction with fixed wayside signals to better accommodate a mix of equipped and unequipped trains, but with negative impact upon capacity as compared with that of the conventional signaling system.

The moving-block concept allows a train to receive a movement authority between any two locations, rather than being constrained to the fixed block boundaries of conventional signaling. Movement limits are updated automatically and more frequently than in conventional systems. This potentially allows train spacing (headway) to be reduced and track capacity to be increased in following move (fleeting) scenarios and certain "bottleneck" situations, such as where track has been downgraded or returned to service after maintenance.

Standalone PTC also has the potential to decrease train control system life cycle cost by reducing the amount of wayside vital equipment required (signals and track circuits).

The NAJPTC project also tackled many of the most challenging issues in the development, refinement, and testing of PTC, including:

- How to determine train location and turnout decisions with safety-critical dependability,
- How to predict enforcement braking distance accurately enough that a train will not go past the target, but not be stopped far short of the target either,
- How to verify train consist characteristics, and
- How to meet PTC system performance requirements given the performance limitations of mobile radio communications.

Summary of Benefits

Benefits derived from the NAJPTC project are:

- By integrating inertial sensors with DGPS, tachometer readings, and map matching, NAJPTC's onboard location determination system increased the ability to dead reckon in areas lacking satellite coverage (such as in tunnels or "urban canyons"), significantly improved track resolution ability, and improved the detection of failure modes over systems that do not incorporate inertial sensors.
- Portions of the NAJPTC system's hardware and software implementation have been reused by other PTC projects.

- Open specifications/design documents from the NAJPTC project have been utilized in other PTC projects.

- The NAJPTC system made greater use of commercial, off-the-shelf hardware and software components than prior vital train control systems.

- NAJPTC was the first project to apply new FRA rule (Title 49 Code of Federal Regulations Part 236, Subpart H). Its safety case (Product Safety Plan, or PSP) provided a template and source material for other PTC projects.

- Being the first to attempt many new and complex train control approaches, NAJPTC testing in Illinois identified a number of design challenges for which solutions were developed and from which valuable lessons were learned (summarized below), benefiting other PTC projects.

Design Challenges and Solutions

Location Determination, and Track Discrimination and Entry Point Protection. The NAJPTC system uses a combination of technologies to address these issues. NAJPTC's location determination system features a multiple-sensor, inertial navigation system (INS) design with diverse self-checking for safety. When temporarily out of DGPS signal coverage, the INS components allow the system to continue operating by dead reckoning.

Consist Determination and Verification. The NAJPTC system design addresses the problem of uncertain freight train consist characteristics by using two modes: Unconfirmed and Confirmed. When a train is initialized, it enters Unconfirmed Consist mode. When sufficient data becomes available for NAJPTC to verify the consist characteristics with adequate integrity for safety-critical purposes, it transitions to Confirmed Consist mode.

Mobile Radio Communications. Based on preliminary analysis and requirements, the Advanced Train Control System (ATCS) Specification 200 standard was the RF data link selected for the NAJPTC project. Evolving requirements proved the 1980's-era ATCS data radio system's performance insufficient for NAJPTC's needs. Various potential solutions were assessed, and ultimately a separate project was initiated to specify the requirements, to develop, and to test a new generation interoperable higher performance data radio system suitable for use with PTC systems.

Lessons Learned

The NAJPTC project was one of the most complex system development/integration projects undertaken to date. The complex, highly distributed system included mobile nodes and was required to meet stringent safety, availability, and performance requirements. The requirements for NAJPTC far exceeded those of any train control system previously implemented.

In addition to invaluable technical results described in this report, other lessons learned include: the necessity for incremental development of such complex systems; the need for thorough and unambiguous specifications; ensuring that the system developer thoroughly understands the system requirements as well as the underlying rationale and train operations; open communication and a cooperative working relationship between the railway and system developer; early test planning; proper rigorous sequence of development steps; having a productive test environment; milestones to demonstrate visible and quantifiable progress during development; maintaining focus on system performance; the need for more adaptive and robust braking algorithms.

Critical Milestones

The NAJPTC project was a multiyear effort with phased development milestones staged according to software builds, each of which adds features to the previous one:

- Build 1: Location determination, reporting, and tracking; Office, onboard, and communications infrastructure.
- Build 2A: PTC Integrated Mode operation at 79mph; Track bulletins; Predictive and reactive enforcement.
- Build 2B: PTC Standalone Mode operation; Crossing advance activation; High-speed (110 mph) passenger train operation; Upgraded RF communications.
- Build 3: Verification of consist length and weight; Pacing; Roadway worker terminal; Functional negotiation; Integral defect detectors; Emergency braking enforcement; Display of predictors; Online track database update capability; and Cab signal interoperability demo.

Due to the difficult design challenges, the project was terminated before the completion of Build 2A because IDOT wanted to begin high-speed operation sooner than would be achievable with the PTC approach. Consequently, Builds 2B and 3 were not fully implemented and tested, although requirements and much of the design was done.

Conclusions

CBTC offers the promise of significant potential benefits in railroad safety, capacity, and efficiency. This report has identified key issues encountered on the NAJPTC project, along with chosen solutions and lessons learned. The experiences gained from this project have benefited other PTC developments and have led to the inception of subsequent projects to further address issues identified on the project.

1.0 Background

The Federal Railroad Administration (FRA), Association of American Railroads (AAR), and the Illinois Department of Transportation (IDOT) jointly funded the North American Joint Positive Train Control (NAJPTC) project, and TTCI, a wholly owned subsidiary of the AAR, managed the project. The project is also known as the Illinois Department of Transportation Positive Train Control (IDOT PTC) project.

1.1 Project Objectives

The NAJPTC project had the following stated objectives:

- Develop, test, and demonstrate PTC capabilities, including moving block operations, interoperability, and advance activation of highway crossing devices in a corridor with both freight and passenger train service.
- Meet the safety objectives of:
  - Preventing train-to-train collisions, by preventing trains from violating their authority limits,
  - Enforcing speed restrictions, including civil restrictions and temporary slow orders, and
  - Protecting roadway workers and their equipment operating under specific authorities, by preventing trains from entering work limits before the train crew has acknowledged that they have contacted the employee in charge (known as EIC).
- Provide for industry interoperability (between railroads or different territory types within a railroad), demonstrate safe operation of locomotives equipped with interoperable systems, and enable equipped trains operating from different railroads to enter a foreign railroad at track speed.
- Provide a cost-effective design to enhance prospects for deployment.

1.2 PTC System Overview

The NAJPTC system was installed and tested on a 120.7-mile segment of the Union Pacific (UP) railroad in Illinois, referred to as the NAJPTC line, as Figure 1 illustrates. This line is part of IDOT's proposed high speed rail corridor extending from Chicago on the north to St. Louis on the south, a distance of 280.5 miles. The segment selected for the NAJPTC system extends from south of Mazonia, Illinois, (milepost 62.6) to the south end of Ridgely Yard (milepost 183.3) just north of Springfield, Illinois (milepost 182.0).

The NAJPTC line operates under centralized traffic control (CTC) and follows the General Code of Operating Rules (known as GCOR). The line consists of single track with sidings for meets and passes as well as spurs and industrial sidings. Numerous highway crossings exist on the line, most of which were equipped by the NAJPTC project for radio-based advance activation to accommodate high-speed passenger trains without having to extend detection circuits. Trains operating on this line are UP freight trains (through and local) and Amtrak passenger trains. The line included interlockings at crossings with foreign railroads. The NAJPTC system was designed to operate under these conditions.

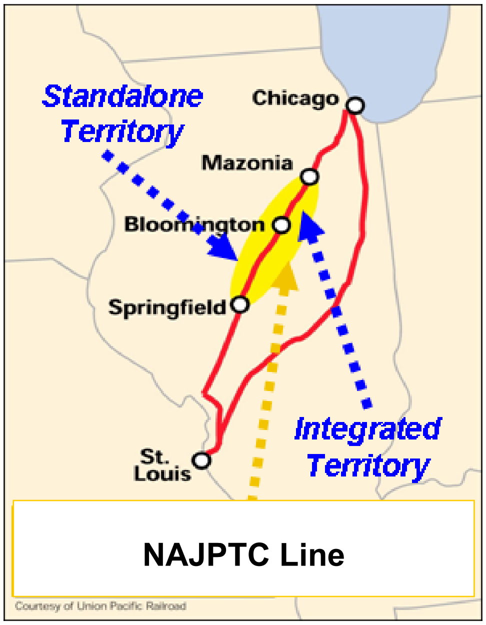


Figure 1. Testing of NAJPTC was in the State of Illinois

The 120 miles of PTC-controlled territory was divided into two categories of roughly 60-miles each: PTC integrated territory and PTC standalone territory. PTC standalone territory was intended to demonstrate the capacity improvements achievable with moving block operation. In addition to the incremental moving block authority limits (applicable to PTC trains only), trains on PTC integrated territory were additionally constrained by conventional fixed signals. Consequently, PTC integrated territory_would not show capacity improvements, but was to demonstrate efficient handling of unequipped trains mixed with PTC-equipped trains.

A third segment of track, the territory between Chicago and Mazonia, was known as PTC-monitored territory. In this area, PTC trains were monitored only for location and speed.

The key elements of the communication-based train control architecture of the NAJPTC system include:

- Mobile data radio, onboard computer, onboard display, locomotive interface, and location determination on each locomotive,

- Server in the dispatch center,
- Wayside interface units at signals, switches, train defect detectors, railroad crossings, and highway crossings, and
- Roadway worker terminal on roadway vehicles.

Figure 2 shows each of the subsystems and their main functions. PTC functions are modular to allow tailored implementation for each railroad or territory. Functionality negotiation capabilities permit trains to automatically adjust to the specifics of each deployment infrastructure. This, along with an open architecture, facilitates interoperability (operating one railroad's locomotive on another railroad's track under PTC) and migration (supporting different levels of functionality at various stages of evolutionary implementation).

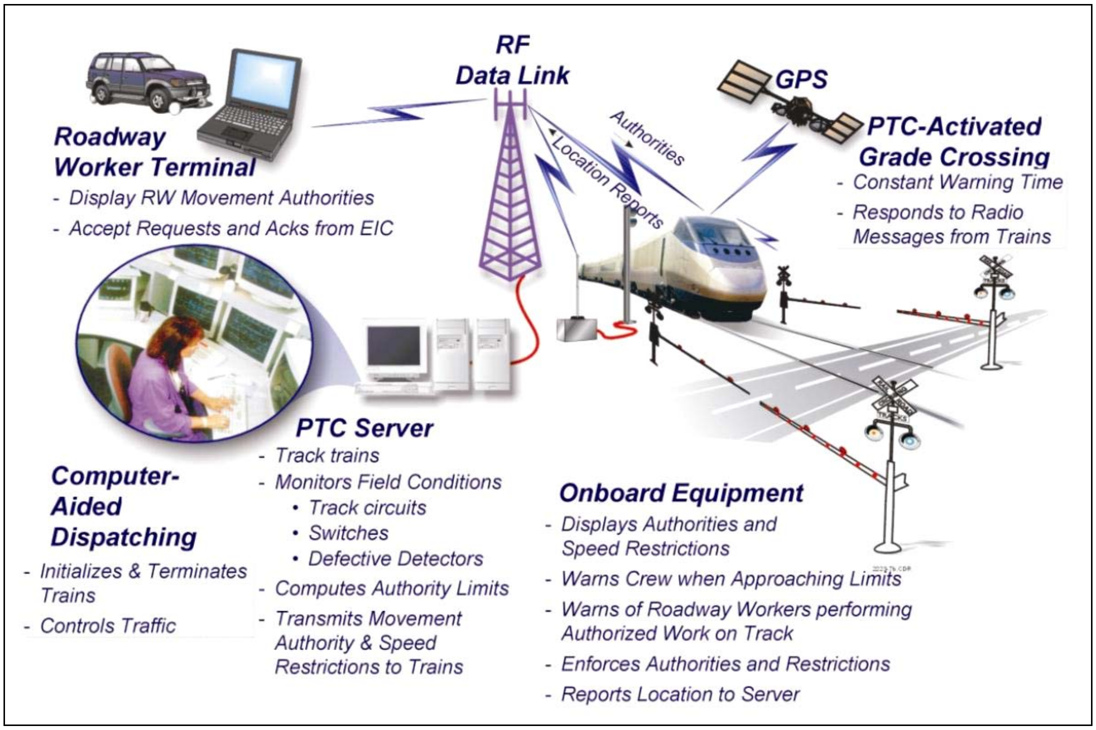


Figure 2. PTC System Architecture

The PTC system architecture is based on the moving block concept (whether integrated with fixed block signals as in integrated territory or operating in standalone territory). This means that a movement authority for a train can be issued between any two unoccupied track locations, rather than being constrained to fixed block boundaries as with conventional signaling. As Figure 3 shows, this has the potential to allow train spacing (headway) to be reduced and track capacity to be increased in following move (fleeting) scenarios and certain bottleneck situations, such as where track has been downgraded or returned to service after maintenance.

Appendix A contains photographs of the NAJPTC system elements along with a legend for the onboard display.

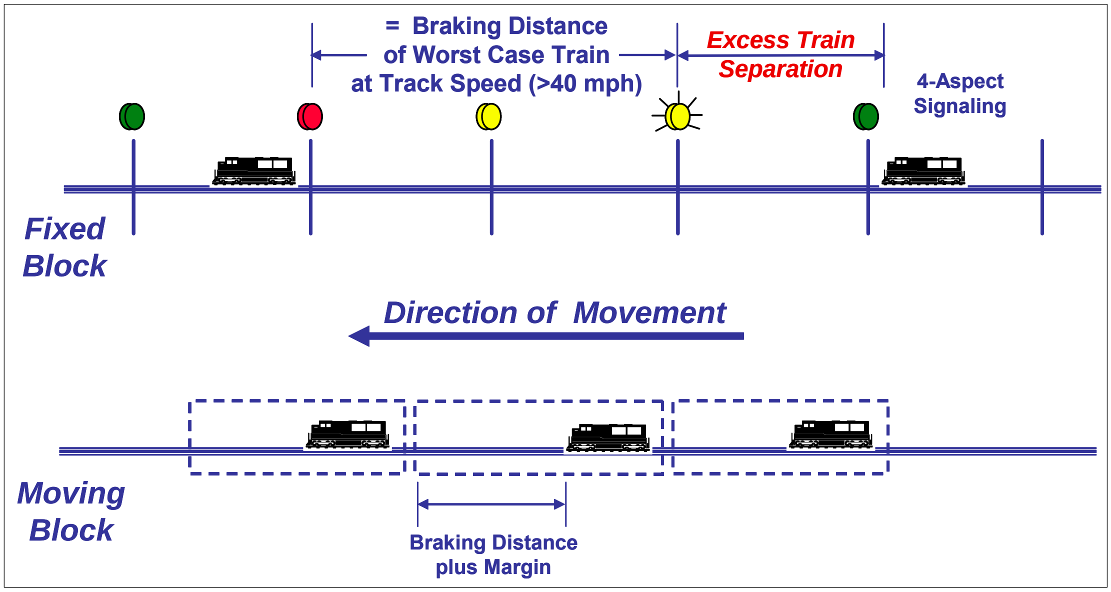


Figure 3. Moving Block has the Potential to Reduce Headways

NAJPTC system development followed a phased plan:

Build 1:

- Office, onboard, and communications infrastructure, and
- Location determination, reporting, and tracking.

Build 2A, a test build including all Build 1 functionality plus:

- PTC integrated mode operation at 79 mph,
- Track bulletin conditions,
- Authority management in NAJPTC—integrated territory, and
- Predictive and reactive enforcement.

Build 2B for revenue service operation including all Build 2A functionality plus:

- Implementation in NAJPTC—standalone territory,
- Crossing advance activation,
- High-speed passenger train operation (increase from 79 mph to 110 mph), and
- Operation with upgraded RF communications for reduced fail-safe latency and higher throughput.

Build 3:

- Integration of high-speed defect detectors,
- Remote entry of roadway worker requests,

- Pacing implementation and testing,
- Emergency enforcement braking implementation and testing,
- Cab signal interoperability demo,
- Confirmed consist approach,
- Functional negotiation capability testing,
- Display of predictors, and
- Online track database update capability.

The NAJPTC project was terminated before the completion of Build 2A because IDOT needed to begin high-speed operation sooner than would be achievable, given the difficult PTC design challenges remaining to be solved. Consequently, Builds 2B and 3 were not fully implemented and tested, although requirements and much of the design was done. See Appendix B for further details of NAJPTC functionality that was implemented and tested.

2.0 Definitions

The terms and definitions listed below are specific to the NAJPTC project and may or may not conform to definitions of similar terms used in other contexts.

Automatic Equipment Identification	An automated scanning and tracking system that reads radio frequency tags mounted on locomotives and rolling stock using wayside scanners.
Automatic Train Control	A system to enforce compliance with cab and wayside signal indications. If the train exceeds a predetermined speed for a given signal indication and speed is not reduced at a sufficient rate, brakes are automatically applied.
Block	A length of track: • between consecutive block signals, • between a block signal and the end of block system limits, or • in Automatic Train Conrol, limits the use of which is governed by cab signals and/or block signals.
Block Signal	A fixed signal at the entrance of a block that governs trains entering and using that block.
Braking Algorithm	The algorithm used to predict a train's braking performance, based on such factors as train length, train weight, braking characteristics, speed, and grade.
Bulletin	Information concerning speed restrictions, work limits, or other instructions relayed to train crews. In General Code of Operating Rules (GCOR), these include Form A, Form B, and Form C bulletins.
Busy Bit	Link access protocol similar to carrier sense multiple access (CSMA) but for duplex channels. Base stations transmit bits indicating whether or not the inbound channel is busy. A node wanting to transmit to that base station uses this information in determining when to transmit.
Centralized Traffic Control	A block system that uses block signal indications to authorize train movements.
Communicating Train	A train that includes a controlling locomotive equipped with PTC equipment that is functional in communication with the PTC communications network. Where the word train is used in a requirement, it is assumed to be a communicating train unless it is specifically described as noncommunicating (see Noncommunicating Train below).
Computer-Aided Dispatch	A system that provides rail dispatchers with a dynamic display of territory and may automate features such as meets and passes, train tracking, and routing.
Configuration Management	A process that addresses revision control measures for products, material modification of hardware and software, and methodology to demonstrate that the proper and intended product configuration, including the actual functional and physical characteristics, are maintained.

Confirmed Train	A train whose length and weight have been verified in a vital manner.
Consist	The set of cars and locomotives comprising a train.
Control Point	The location of absolute signals controlled by a control operator.
Distributed Power	The practice of placing locomotives, which can be remotely controlled in the middle or rear of the train, to improve train handling.
Employee-in-Charge	Refers to supervisor of roadway workers working on or about the right-of-way. As used in this document, it refers to the authorized user of the Roadway Worker Terminal (RWT).
Enforcement	The act of applying train brakes automatically and safely to keep the train in compliance with the constraints of allowed speed, track occupancy, authority limits, and direction of travel imposed by a control system.
End-of-Train device	A device that monitor's the train's air brake system and train integrity. It has a flashing red light (at night) and provides the capability to make an emergency brake application from the rear of the train.
Engineer	The qualified and responsible operator of a locomotive.
Fail Safe	A design philosophy applied to safety-critical systems such that the result of hardware failure or the effect of software error shall either prohibit the system from assuming or maintaining an unsafe state, or shall cause the system to assume a state known to be safe (IEEE 1483).
Fixed Block Operation	A method of operation where authorities are issued to fixed wayside points, such as mileposts, switches, roadway signal locations, and stations.
Full Service Application	An application of the brakes resulting from a continuous or split reduction in brake pipe pressure at a service rate until brake cylinder pressure is equalized with auxiliary reservoir pressure.
Functionality Negotiation	The process of identifying the highest level of common functionality that can be achieved safely by onboard and off-board PTC systems.
General Code of Operating Rules	A set of operating rules used by a number of North American railroads. These rules are meant to promote safety, and cover topics including general employee responsibilities, signals and their use, and procedures for the safe movement of trains.
High Accuracy-Nationwide Differential Global Positioning System	An upgrade to differential global positioning that provides the capability to broadcast corrections to the global positioning system (GPS) over long ranges to achieve a better than 10 centimeter (cm) (95 percent) accuracy throughout the coverage area.
Location Determination System	The system onboard the locomotive that determines the train's location and speed.

Management Information System	The component of the railroad's information system that maintains data on train consists, schedules and may also provide the means for issuing bulletins.
Movement Authority	Permission given to a train crew or work crew to occupy a track and move within defined limits.
Moving Block Operation	A method of operation in which authorities are issued to the rear of a preceding communicating train in following move operations instead of to fixed block boundary locations.
Noncommunicating Train	A train that that does not include a PTC-controlling locomotive or one that includes a PTC-controlling locomotive equipped with PTC onboard equipment that has failed or is not in communication with the PTC communications network.
Office	A railroad office location from which rail operations are controlled and monitored. An office may control a whole railroad or a single division. An office may be completely manual using pen, paper, and voice communications, or may be highly automated with sophisticated computer support.
On Sheet	The act of reporting the arrival, departure, or passing of a train at a specific location.
Operating Rules	The set of rules specifying the operation of a railroad, which are meant to promote safety, and cover topics including general employee responsibilities, signals and their use, and procedures for the safe movement of trains.
Positive Train Control	A train control system that meets the three safety objectives defined by the Railroad Safety Advisory Committee: Prevention of train-to-train collisions, prevention of derailments due to train operation in excess of permitted speeds, and protection of roadway workers operating within the limits of their authorities.
Predictive Enforcement	The action of enforcing a train to prevent a predicted violation of authority, restriction, or speed limit that would otherwise occur.
Product Safety Plan	A detailed description of a PTC system and its operation, including hazard logs, human factors analysis, and risk assessment. A PSP is required to be submitted to FRA for approval to allow a PTC system to be operated in revenue service.
Reactive Enforcement	The action of enforcing a train after violation of the limits of its authority, restriction, or speed limits.
Restricted Speed	A train operating speed that allows the locomotive crew to stop the train within half of the range of vision, short of a train, engine, men, or equipment fouling track, stop signal, derail, or improperly lined switch, and looking out for broken rail, not to exceed the maximum speed defined by the rulebook in force. A typical maximum speed allowed under restricted speed authority is 20 mph.

Reverse Move	A movement by the locomotive or portion of a train in the opposite direction of its unidirectional authority that results in movement of the rear of the train in the direction opposite of the authority. An example of a reverse move is a train that is moving its entire consist in reverse.
Risk	An expression of the possibility/impact of a mishap in terms of hazard severity and hazard probability. (Military Standard 882C)
Risk Analysis	The process determining, either quantitatively or qualitatively, the measure of risk associated with (1) use of the product under all intended operating conditions or (2) the previous condition. (49 CFR 236 Subpart H)
Roadway Workers	Maintenance and inspection personnel that require access to areas of the railroad including track to perform their assigned duties.
Safety Critical	A designation applied to a function, a system, or any portion thereof, the correct performance of which is essential to safety of personnel and/or equipment, or the incorrect performance of which could cause a hazardous condition, or allow a hazardous condition, which was intended to be prevented by the function or system, to exist. (49CFR236 Subpart H)
Siding	A section of track that leaves a main line and enters back onto it (most often long enough to fit an entire train), which allows one train to move aside while another passes.
Signal Block	See Block
Speed Restriction	A speed limit that may be permanent or temporary for a certain location or type of train on the basis of direction of travel or track on which the train is operating.
Temporary Speed Restriction	A bulletin that prescribes a speed restriction over track within certain limits. Temporary speed restrictions are applicable to the entire length of a train, unless qualified as "head-end only" or "stop and inspect."
Track Circuit	A circuit that allows for the detection of train occupancy within a section of track.
Track Discrimination	Determining which track a train is on when it is within multiple-track territory.
Train	One or more locomotives carrying a marker with or without cars.
Transportation Technology Center, Inc.	A transportation research, testing, and consulting company providing emerging technology solutions for the railway industry throughout North America and the world (a wholly owned subsidiary of the Association of American Railroads).
Vital function	A function in a safety-critical system that is required to be implemented in a fail-safe manner. (IEEE 1483)
Wayside Interface Unit	A device that provides remote monitoring and control of wayside devices.
Work Limits	The locations between which a work authority has been issued.

3.0 Benefits from the NAJPTC Project

In addition to the safety objectives listed in Subsection 1.1, the NAJPTC system was designed to accommodate 110-mph passenger trains. In addition, vital, moving block (standalone) PTC has the potential to increase railroad capacity by reducing excess headway as compared with fixed block signaling and by reducing congestion via pacing. It also has the potential to decrease train control system life-cycle cost by reducing the amount of wayside vital equipment required.

3.1 Potential Headway and Capacity Benefits of Vital, Moving Block PTC

Although development of the standalone mode (i.e., vital, moving block PTC) was a Build 2B work item that was not completed before the project was terminated, the design progressed far enough to quantify the standalone mode's parameters and braking algorithm margins. This in turn allows projection of the potential reduction in headway and potential increases in capacity of the NAJPTC moving block implementation as compared with a conventional 4-aspect signaling system. Since Build 2B was not completed, the potential benefits of moving block have not been proven by actual implementation and field testing.

The potential headway reductions and potential capacity increases to be gained by using a vital, moving block PTC system were analyzed with a variable warning time to the engineer (indicating that braking enforcement was imminent) for a loaded 123-car grain train considering various block lengths, warning times, grades, and brake algorithm margins. Trains were modeled operating in a following move scenario at the same speed (e.g., double track current-of-traffic, or fleeting on single track).

The mode of operation for use in NAJPTC Standalone Territory was a *hybrid* between fixed and moving block train control. The reason for this hybrid configuration is that two enabling technologies were unavailable that are necessary to obtain significant benefits from moving block at speeds above 49 mph. The two enabling technologies are (1) a vital train consist determination and integrity monitoring system (to detect pull-aparts) and (2) a broken rail detection system that does not impose traditional fixed block train separations (headways). In the absence of these two enabling technologies, the NAJPTC project depended on conventional track circuits (associated with the signaling system) to address train consist/integrity and broken rail detection in standalone mode (as well as integrated mode). To achieve the maximum potential headway reduction from moving block operation, a more accurate brake-distance prediction algorithm would also be required.

As illustrated in Figure 4, NAJPTC's hybrid moving block/fixed block concept enforced a 20 mph speed restriction (upper limit of a restricted speed restriction) through an intermediate block that was occupied or that contained a broken rail, rather than enforcing an authority limit (stop) at the last reported rear end location of the leading train. This dependency on track circuits significantly limited the potential capacity or headway improvement otherwise attainable from moving block operation. Figure 5 shows the degree of performance improvement achievable with the hybrid moving block/fixed block mode of operation.

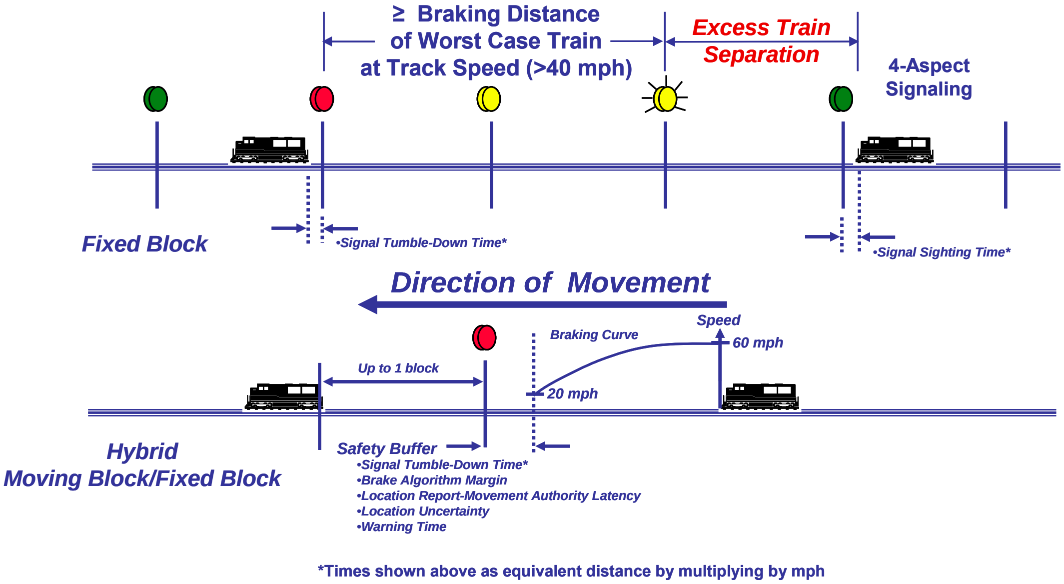
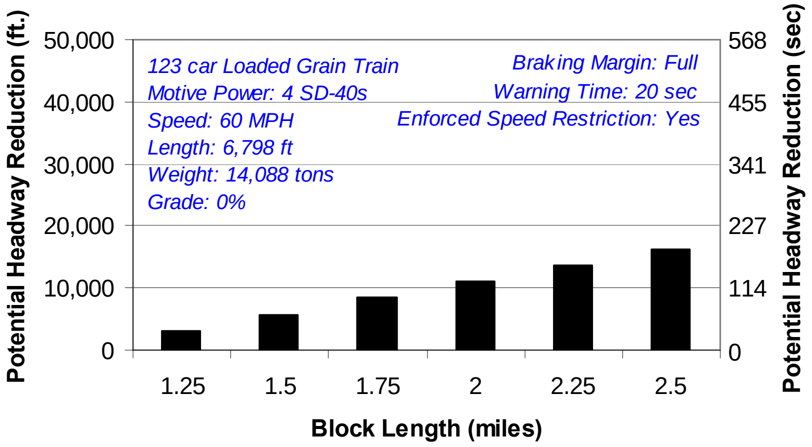


Figure 4. Relationship of Moving Block and Conventional Signaling Parameters Used in Analysis of Potential Headway Reduction and Capacity Increase for a Hybrid Moving Block/Fixed Block PTC System

The standalone mode of NAJPTC could also be configured to operate in *pure* moving block mode, i.e., where train separation is governed primarily by safe braking distance to the train ahead without any constraints from a signaling system. This mode of operation offers much greater potential headway and capacity benefits but requires two currently unavailable enabling technologies (mentioned earlier), or else it can only be used at speeds below 50 mph.

For pure moving block operation, the performance was modeled for the same loaded 123-car grain train traveling 60 mph on a level route, using a block length of 2.5 miles, a 20-second warning time, and the NAJPTC brake algorithm margin.



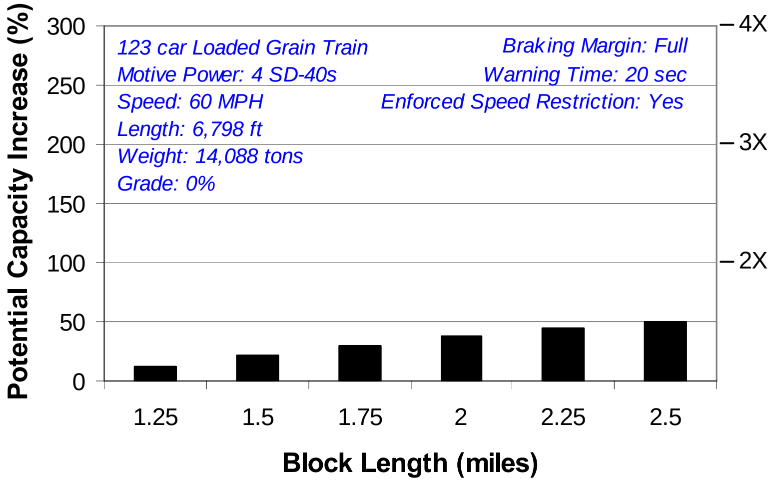
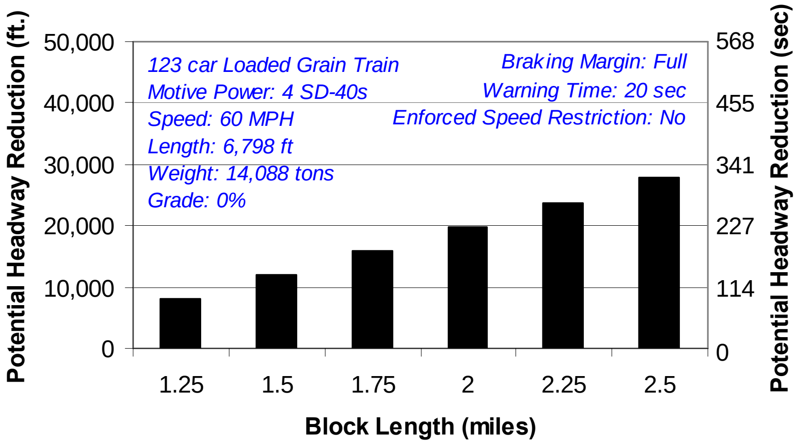


Figure 5. Potential Headway Reduction and Capacity Increase for a Hybrid Moving Block/Fixed Block PTC System vs. 4-Aspect Signaling for a Typical Grain Train

The analysis shows that a vital, moving PTC system could provide a headway reduction of 27,745 feet, or 315 seconds, between trains for this scenario, corresponding to a potential capacity increase of 133 percent (where a capacity increase of 100 percent corresponds to a doubling of capacity) when compared to a conventional, 4-aspect signaling system using a block length of 2.5 miles. This amount of capacity increase is only achievable in scenarios where trains operate in close following moves, such as double track or fleeting. In single track, nonfleeting scenarios, where meets occur frequently, the potential capacity improvements from moving block PTC are not as significant.

The potential savings in headway and increase in capacity can be quantified for this same scenario considering other block lengths. Figure 6 shows the results for block lengths ranging from 1.25 to 2.5 miles (in increments of a quarter mile).



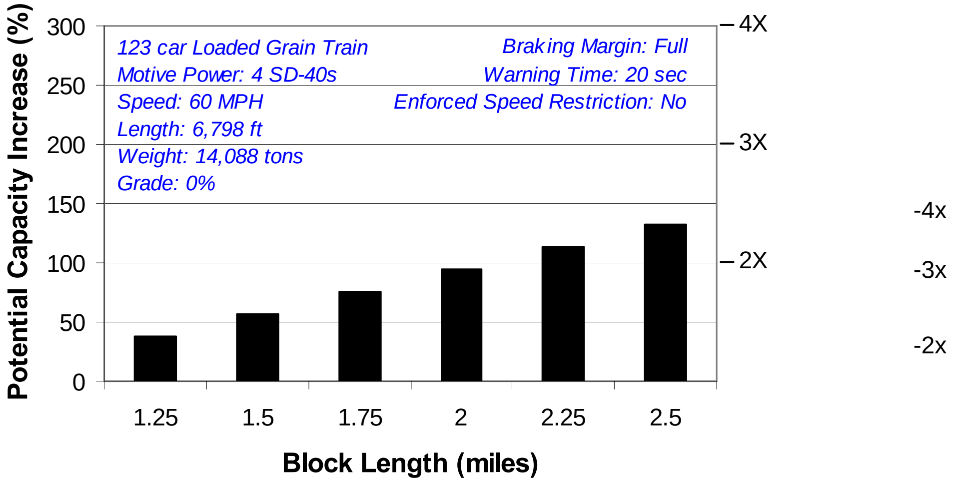


Figure 6. Potential Headway Reduction and Capacity Increase for a Vital, Moving Block PTC System vs. a 4-Aspect Signaling System for a Typical Grain Train

The results show that in spite of the significant conservatism (margin) that was designed into the NAJPTC braking algorithm (to allow for uncertainties in train characteristics), the potential capacity increases, or headway reductions are significant. Appendix C includes results for additional scenarios comparing performance under moving block versus conventional train control.

It should be noted that while moving block ("standalone") PTC has the potential to increase railway capacity and reduce headways, the integrated mode (or an overlay PTC system) cannot increase capacity—it can only degrade capacity and headway (due to braking algorithm margin and system delays), because it imposes additional constraints beyond those imposed by the conventional signaling system. This degradation is expected to diminish, however, as accuracy of predicting braking distance improves by future development.

3.2 Additional Benefits Provided by Vital, Moving Block PTC

Vital, moving block PTC has the potential to provide benefits in addition to those already cited.

One of these potential benefits is faster recovery from track outages or temporary speed restrictions. With vital, moving block PTC, there would be no holding back a following train at an absolute signal while waiting for the entire block to be cleared by the leading train. Instead, the following train could follow the leading train at safe braking distance. Additionally, no signal-imposed speed restriction (e.g., restricted speed) for trains following within the same block would occur.

Another potential benefit provided by vital, moving block PTC would be that there would be less time lost during overtake or pass situations. When a faster train is following, the closing up process when entering the meet could be tighter, and the slower train would be able to depart from the siding sooner after the pass.

Installing a vital, moving block PTC would also eliminate the need for wayside signals and their associated cost and maintenance. Where broken rail detection would not be required or where alternatives exist, no need for track circuits would be required. Consequently, reduction or elimination of costly vital wayside equipment is anticipated as a potential long-term benefit when vital, moving block (standalone) PTC is fully deployed on a corridor.

3.3 Benefits Derived from the NAJPTC Project

In addition to the lessons learned (addressed later), the benefits achieved by the NAJPTC project include:

- By integrating inertial sensors with DGPS, tachometer readings, and map matching, NAJPTC’s onboard location determination system (LDS) has increased the ability to dead reckon in areas lacking satellite coverage (such as in tunnels or “urban canyons”), significantly improved track resolution ability, and improved the detection of failure modes over systems that do not incorporate inertial sensors.

- Portions of the NAJPTC system’s hardware and software implementation have been reused by other PTC projects.

- Open specifications/design documentation from the NAJPTC project has been used in other PTC projects.

- Being the first to attempt many new train control approaches, NAJPTC testing in Illinois identified a number of implementation issues from which valuable lessons have been learned and solutions developed, benefiting other PTC projects (see Section 5.0).

- The NAJPTC system makes greater use of commercial, off-the-shelf hardware and software components than did prior vital train control systems, paving the way for lower life cycle costs.

- First freight train control system to attempt vital tracking of non-PTC trains (integrated with PTC trains) via track circuits from which valuable lessons were learned and are addressed in this report.

- First project to apply new FRA rule (49 CFR, Part 236, Subpart H), resulting in a better understanding of what is required to apply it to an actual development project.

- Safety case (product safety plan, or PSP) provided a template and source material for other PTC projects.

4.0 Design Challenges

Many challenges have existed and will continue in the development, refinement, and testing of PTC. The following are among the most challenging issues that have been encountered so far in its development:

- How to determine train location and make turnout decisions (track discrimination) with safety-critical dependability,
- How to predict enforcement braking distance accurately enough that a train will not go past the target nor be stopped far short of the target,
- How to verify train consist characteristics, and
- How to meet system performance requirements given the performance limitations of mobile radio communications.

The first three items above are particularly difficult to accomplish with the necessary degree of integrity required for vital train control. The potential solutions to challenging problems like these often have associated life-cycle costs and/or operational implications. Therefore, the railroad(s), system engineer, and system developer must carefully analyze and select the most appropriate solution.

Further descriptions of the above issues and others along with the approaches selected for the NAJPTC project are presented below.

4.1 Location Determination, Track Discrimination, and Entry Point Protection

4.1.1 The Challenge

A fundamental concept common to PTC systems is that trains must continually and accurately determine their location on board and transmit it to an off-board server rather than having their location determined coarsely by occasional wayside devices such as track circuits or axle counters. Without accurate train location determination in a PTC system, uncertainty buffer distances must be increased, resulting in productivity impacts including increased train headways, less usable siding capacity, and stopping trains shorter of signals than necessary.

In addition, it is extremely critical to know which track each train is occupying in areas of parallel track. The function of identifying the correct track is referred to as “track discrimination.” The challenge in train location determination and track discrimination is in meeting the very high-integrity requirements required for safety. Without high-integrity track discrimination, a PTC system must depend upon human input, which increases safety risk. Additional ramifications of various solutions are addressed below.

4.1.2 Potential Solutions

An obvious solution to the location determination and track discrimination problem might seem to be installation of a differential global positioning satellite (DGPS) receiver on board each locomotive. DGPS can provide very high-integrity location determination based on multiple satellites with accuracy on the order of that needed to meet the PTC requirement for along-track accuracy of better than 10 ft with 99 percent confidence. However, DGPS by itself is not accurate enough for high-integrity track discrimination of the nature required for a vital train control system. Specifically, the probability of correct track discrimination where parallel tracks may be 11.5 ft apart is less than 0.99 with ordinary DGPS alone; whereas, the requirement for train control is on the order of 0.999999. Also problematic is when DGPS coverage is temporarily lost, most often because of signal blockage in certain locations.

Monitoring all switches and tracking train movements through switches can solve the track discrimination problem with DGPS. With this approach, however, the problem of DGPS blockage remains. This problem can be addressed to some extent by using locomotive tachometer information to allow the LDS to coast (dead reckon) through temporary DGPS signal outages. However, this solution only works for limited DGPS signal outages because tachometer distance error accumulates with wheel slip and creep.

Although the combination of DGPS, tachometer, track database, and switch monitoring may work sufficiently for non-vital overlay PTC systems and for vital systems over a limited corridor, more than 50,000 miles of track in the United States do not have monitored switches; economics generally will not justify equipping all of them with monitored switches solely to support PTC.

The solution used in the European Train Control System is to install transponder tags at strategic track locations (e.g., on each leg of a turnout) and to have a tag reader on board each locomotive used in conjunction with the tachometer. This approach can perform reliable track discrimination and does not suffer from signal blockage of the DGPS nature. Whereas this solution is practical in some scenarios, it is not considered practical for general use on U.S. freight railroads, which operate over 95,000 miles of track. The issues have to do with the costs and logistics of installing and maintaining tags, the configuration management associated with their use (e.g., ensuring that tags with a specific serial number are located correctly), and preventing their vandalism on many miles of track, as well as maintaining tag readers underneath locomotives.

Whether a satellite or transponder-based approach is used, knowledge of switch position is needed for two purposes: (1) for display to the train crew on board and (2) for enforcement of authorities and speed restrictions. Consequently, a need exists to monitor turnouts vitally (either directly or through detection of track circuit shunting) in areas where train speed can be high (e.g., over 49 mph) or density can be high, regardless of the type of locomotive-based LDS employed.

4.1.3 NAJPTC Approach and Rationale

The NAJPTC LDS approach uses the combination of technologies illustrated in Figure 7, which has been selected to address the above issues.

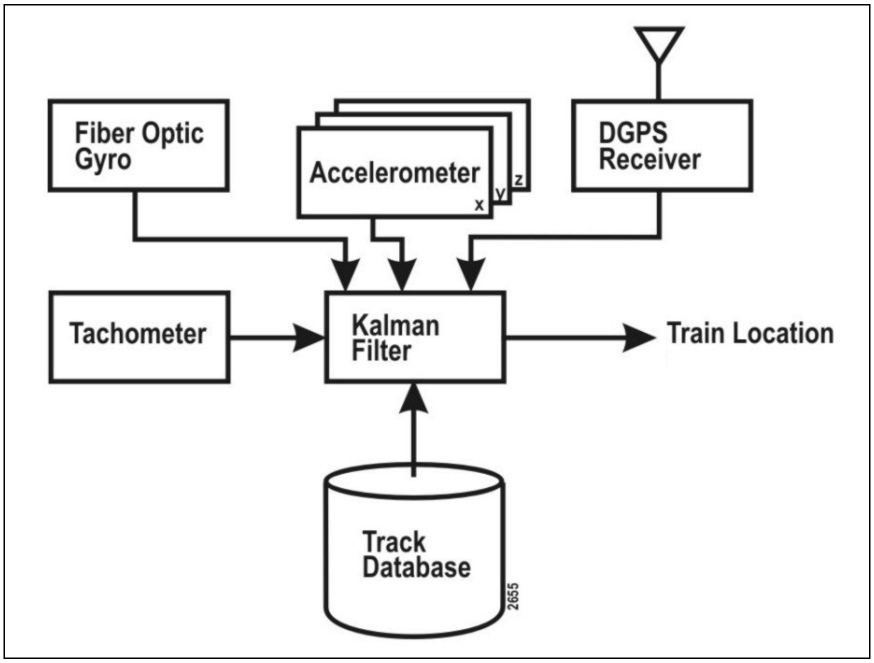


Figure 7. NAJPTC Onboard Location Determination System

NAJPTC's multiple-sensor, inertial navigation system (INS) design handles the various LDS challenges described above and performs self-checking to maintain safety. For example, when temporarily out of DGPS signal coverage, the INS components allow the system to continue operating. The gyro provides extremely precise turn rate information to allow dependable turnout decisions (track discrimination) as a locomotive passes through a facing-point turnout. This compensates for the insufficient accuracy of DGPS alone to reliably perform track discrimination. The gyro also helps to correct tachometer errors (due to wheel slip and creep) as the train passes through curves. This is useful in areas lacking DGPS coverage, such as in tunnels and urban canyons. The accelerometers also help in verifying turnout decisions as well as determining direction of movement (forward versus reverse), which most tachometers are not designed to detect. Additionally, for the NAJPTC implementation in Illinois, all turnouts are monitored because of the moderate and high-speed operations on that territory.

One of the more challenging requirements of the NAJPTC system was that it prevents unauthorized trains from entering PTC territory, using brake enforcement if necessary. In order for the NAJPTC system to enforce, it first had to be enabled, and to enable, it needed to know which track the train occupied (track discrimination must have occurred). This could be technically very difficult for trains initializing outside of PTC territory, due to the lack of prior continuous location tracking history up to that point. The pre-enable track discrimination problem had to be solved in each of three different scenarios (referred to as "POD 1", "POD 2", and "POD 3", where POD stands for "Point Of Discrimination"). The POD 1 scenario was the easiest to accommodate. In POD 1, no other tracks were within 50 feet of the entry track, so the LDS could definitively resolve track based on GPS and the track database alone. If, however, a train initializes on one of multiple closely spaced tracks, onboard LDS systems generally are not able to verify which track the train is occupying with a high enough level of safety integrity until the locomotive moves through a track feature with a LDS-detectable signature profile (e.g., a turnout or a unique curve). NAJPTC correlates location reports with track circuit occupancy information when available and sufficient to resolve this initialization ambiguity (POD 2). Otherwise, the ambiguity in this POD 3 scenario would not be resolved until alternative methods are used, such as moving the locomotive through an unambiguous track feature, operator input is obtained, or the system design is modified as described below. The solution for POD 3 scenarios was not resolved or implemented as it was a Build 3 function.

The track discrimination problem at initialization can be further (but not totally) mitigated by having the LDS on board every PTC locomotive enabled and tracking at all times when the locomotive has power available, regardless of whether or not the PTC system has been enabled and initialized. This also requires use of the onboard data radio to verify that the locomotive’s track database is current at all times. This potential POD 3 approach was considered for Build 3. High accuracy nationwide differential global positioning system (HANDGPS), if and when it becomes widely available, would offer a better potential solution, because it would eliminate the need to sometimes rely on human input or passage through a suitable track feature before being able to provide PTC protection to a train.

During Build 1 field testing, NAJPTC’s onboard LDS was shown to meet system performance requirements at speeds ranging from 2 to 110 mph. It consistently made correct turnout decisions well before the train reached the frog of the turnout. Throughout both phases of the project, the LDS consistently performed very well.

4.2 Consist Determination and Verification

4.2.1 The Challenge

PTC requires dependable consist (train makeup) data, particularly train length and weight, to support the following safety critical functions:

- Rolling up movement authority limits in Standalone Territory (moving block),
- Enforcing movement authority limits during reverse moves,
- Predicting braking distance (for enforcement and warnings),
- Predicting future train location (for onboard display and activation of highway crossings), and
- Displaying train length on board.

Although railroads generally have data on every consist, that data may not be dependable and/or timely enough for use in safety critical train control functions. Thus, additional measures need to be taken.

A related issue is that after consist data has been determined, the system must monitor train integrity to know if and when the consist may have changed.

Besides the safety risk associated with non-fail-safe detection of pull-aparts in unsignaled territory, there are productivity ramifications of inaccurate consist determination. These stem from having to assume worst case train consist characteristics that result in increased train headways, less usable siding capacity, and stopping trains shorter of signals than necessary.

4.2.2 Potential Solutions

The potential solutions are based on the possible sources of consist information. Railroad management information systems (MIS) and/or computer-aided dispatch (CAD) systems generally have data on consists. This data is not intended for vital use, so it is not created or stored with the level of integrity necessary for fail-safe applications. Because consist data is provided to PTC from the CAD system (whether originating at CAD or MIS), it is referred to as CAD-supplied. Train crews also have consist information (from the same sources) but it is not generally adequate for train control purposes.

There are a number of wayside devices that can provide various consist information. These include:

- Automatic equipment identification (known as AEI),
- Hot bearing detectors (HBD),
- Wheel impact load detectors (WILD),
- Track circuits.

Today, other than track circuits, not nearly enough of these devices are deployed along U.S. railroads to meet the consist data needs of PTC. Although track circuits have been traditionally used to address these same fundamental issues, they are quite expensive to maintain, and they negate the potential benefits of moving block. Consequently, the elimination of track circuits is a long-term objective that was beyond the scope of the NAJPTC project. An alternative, less expensive, means of mitigating broken rail risk (e.g., detecting rail breaks) to support reduced headways is a key enabler that is not available yet. On most U.S. railroads, the train defects detectors only transmit a synthesized analog voice report to the train over the voice radio.

Another solution that has been proposed is an enhanced end-of-train (EOT) device that would determine train length or location. Some suppliers have added a GPS to an EOT device, but these devices have not been validated for vital PTC applications. Design challenges exist to achieving adequate satellite coverage in the EOT environment (i.e., hemispherical blockage by end of railcar). Also, coupler mounting conditions are much less than rigid given the need for quick, easy connection and disconnection. Moreover, the logistics associated with introducing and maintaining a second type of EOT device into railroad fleets are a deterrent.

An alternative approach is to include a locomotive (equipped with GPS and a data radio to detect and report end-of-train location to the PTC equipment at the front of the train) at the end of each PTC train under the control of distributed power (DP). The rear locomotive can also help manage in-train forces while reducing the length and variance of stopping distance and detecting/reporting pull-aparts. GPS on the rear locomotive can be used to determine rear-of-train location and to compute train length. The economic justification for including a locomotive at the rear of each PTC train would be further increased if that locomotive hosted a broken rail detector.

Derivation of consist data from onboard measurements of train acceleration and/or deceleration characteristics has also been considered. Based on ΣF=MA (sum of the forces equals mass times acceleration) calculations, train weight can be calculated if a train's total horsepower is accurately known. Braking distance estimates for predictive enforcement (one of the key products of consist data) can be verified from samples of routine air brake applications while moving en route. Unfortunately, many trains go a long distance, possibly an entire trip, without applying the air brakes enough to obtain data of relevance to braking distance estimation. Other measures can be taken to improve the accuracy of braking prediction algorithms and to make them more adaptive, including measuring the propagation time of induced brake pipe pressure changes at the EOT during brake application and monitoring the braking efficiency of the train.

An indication of train integrity can be inferred by monitoring rear-of-train brake pipe pressure using standard EOT devices. But not all passenger trains in the United States are equipped with EOTs. More modern passenger trains typically have an electric trainline running through the cars and locomotives that may be able to provide train integrity information, but it does not always run the entire length of the train, particularly when it is made up of newer and older cars.

In dark territory situations where a maximum freight train speed of 49 mph (59 mph for passenger trains) is acceptable, moving block operation may be viable without the need for vital equipment to detect train integrity, train presence, and broken rails (i.e., without track circuits, vital EOTs, etc.), since they're not generally required today (per federal regulations) for operation at these speeds. However, traffic density may be a consideration, per 49CF236 subpart H.

4.2.3 NAJPTC Approach and Rationale

Because of the wide potential variations and uncertainties in freight car consist characteristics, the consist verification challenge lies primarily with freight trains. The NAJPTC system design addresses the problem by using two consist modes: "Unconfirmed" and "Confirmed" . When a train is initialized, it enters Unconfirmed Consist mode. If and when sufficient data becomes available for NAJPTC to verify the consist characteristics with integrity adequate for safety critical purposes, it transitions to Confirmed Consist mode.

In Unconfirmed Consist mode, several conservative measures are taken for safety reasons. Due to potential wrong-side errors (unsafe failure modes), the predictor, which shows the crew the expected location and speed of their train 30 s and 1 min into the future, is not displayed. For similar reasons, the train length is not displayed when the consist is unconfirmed. Until the consist is confirmed, train weight is established as the heavier of (a) the worst-case weight of all train types, and (b) consist weight provided by the CAD system. Authority roll-up behind a train is based on track circuit occupancy indications while in Unconfirmed Consist mode. So, no moving block is behind a train in Unconfirmed Consist mode. This protects the rear end of the train.

A train transitions from Unconfirmed Consist to Confirmed Consist mode if and when its length and weight are measured and found to match the CAD-supplied consist length. If they never match, the train never leaves Unconfirmed Consist mode, thus requiring that the most conservative parameter values continue to be assumed for that train's consist. Train length is measured by correlating occupancy and clearance reports from a monitored track circuit at a control point (referred to as an OS) with time-stamped location reports from the train. The method of measuring weight may be based on monitoring acceleration performance and performing $\Sigma F=MA$ calculations given the total locomotive horsepower, which train crews can confirm.

Once in Confirmed Consist mode, some of the extremely conservative measures applied in Unconfirmed Consist mode are no longer required. Train length and predictors are displayed; authority roll-up is based on confirmed train length, so moving block operation can now occur in Standalone Territory. However, even in Confirmed Consist mode, the variations in train-braking characteristics (e.g., due to train weight uncertainty, brake-rigging efficiency uncertainty, valve type, etc.) are significant. So, a significant amount of margin is still needed when predicting braking distance.

A train transitions from Confirmed Consist back to Unconfirmed Consist mode upon occurrence of certain "consist events." Sample consist events are:

- Pull-apart, as detected by a loss of rear brake pipe pressure or as entered by the crew,
- Discrepancy detected between CAD-supplied consist length and that obtained from track circuits in conjunction with location reports (due to an update from either source), and
- Train stops (this includes when work activities are performed).

For the NAJPTC implementation in Illinois, track circuits remain in place throughout both Integrated and Standalone Territory. This allows the moving block train-integrity problem to be solved by a combination of the following four methods:

1. A speed restriction is imposed behind a train to the end of the block it occupies. The value of this speed restriction is configurable and can be adjusted based on risk analysis.
2. Rear of train brake-pipe pressure is monitored for unexpected loss of pressure.
3. Train crews can indicate a train separation to NAJPTC via the onboard HMI.
4. Train length is measured every time a train occupies and then clears an OS.

Verifying train length and weight to transition to Confirmed Consist mode was planned for implementation in Build 3 of the project. Since Build 3 was not initiated, the NAJPTC system always operated in "Unconfirmed Consist" mode for freight trains. Four worst-case consists were provided for passenger trains, and the train crew was required to select the appropriate one, from the following types:

- Train Type A (maximum speed of 110 mph)—a future high-speed trainset (consist to be determined),
- Train Type B (maximum speed of 110 mph)—a defined combination of Amtrak locomotive(s) and Amfleet, or Horizon cars, baggage cars, or RoadRailer vans,
- Train Type C (maximum speed of 90 mph)—a defined combination of Amtrak locomotives, and Amfleet, Horizon, or Superliner cars, baggage cars, or express cars, including RoadRailers, and
- Train Type D (maximum speed of 90 mph)—all Amtrak trains that do not qualify as Train Type A, B, or C.

The passenger enforcement algorithms used fixed enforcement equations that were based on train type, but independent of train size within the train type. The freight enforcement algorithm computed braking distance using a worst-case consist for Build 2 testing.

Whether using worst-case consist or confirmed consist, the NAJPTC system specification required that freight trains stop short of the enforced target (not overrun) with 99.9995-percent probability. This was probably an excessively conservative requirement. However, it has been adopted for most other PTC systems as well.

Whatever probability is specified for enforcement target overrun, a PTC-braking algorithm must apply an offset (margin) to compensate for the unknown variations in train braking characteristics (e.g., due to unknowns in brake-rigging efficiency, brake valve type, coefficient of friction, train weight, number of operative brakes) to meet this requirement. In other words, the PTC system must apply the brakes earlier than required for a typical train. Figure 8 is an example of the amount of offset required. The example shown is for a grain train of 123 loaded cars, 4 locomotives with 12,000 horsepower total, 6,798 feet long, and weight of 14,088 tons. The offset required in order to meet the

99.9995-percent requirement is 1,762 feet. In other words, the average train with the above stated characteristics would stop 1,762 feet short of an enforced target.

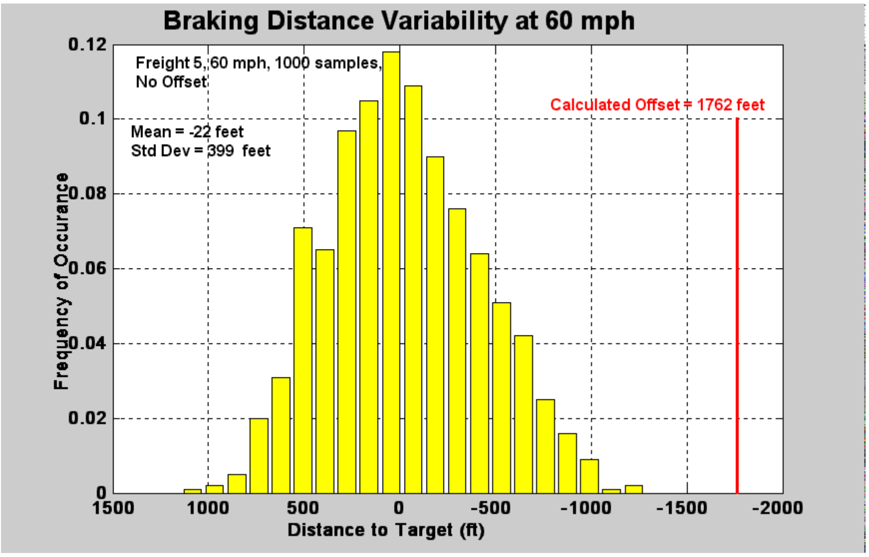


Figure 8. Simulated Braking Distribution Shows that an Average Loaded Grain Train Running at 60 mph Would Be Stopped 1,762 feet Before Necessary by the PTC Braking Algorithm with "Confirmed" Consist

Having PTC assume the worst-case consist at all times for freight train operation, however, would not be practical in revenue operation due to the excessive conservatism this would require in stopping trains (i.e., stopping trains too soon). This is apparent from Figure 9, which shows that 97.3 percent of the time PTC would stop a train operating at 10 to 30 mph more than 500 feet from the target using worst-case consist assumptions for the braking algorithm. Figure 10 shows that 100 percent of the time PTC would stop a train operating at 30 to 60 mph more than 1,000 feet from the target using worst-case consist assumptions for the braking algorithm.

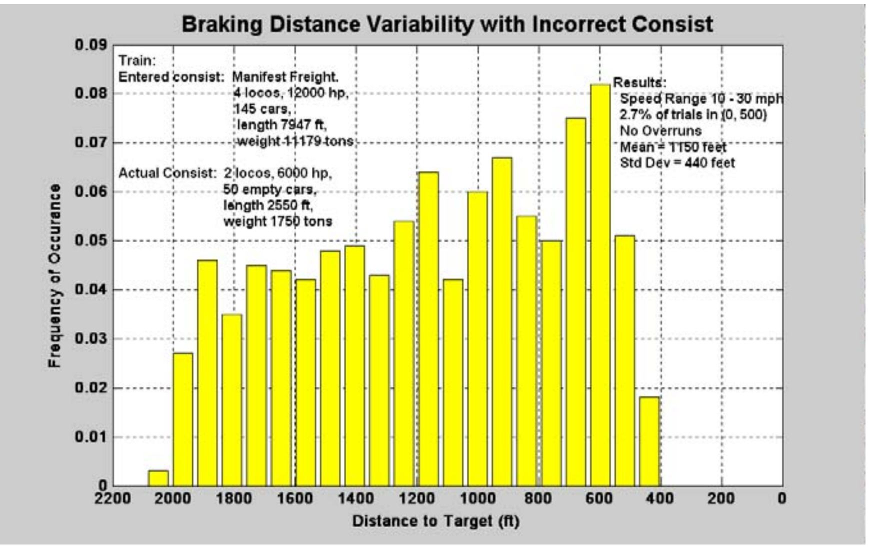


Figure 9. With Worst-Case Consist Assumptions, No Overruns Occur, But a 10–30 mph Train Stops within 500 ft of the Target only 2.7% of the Time

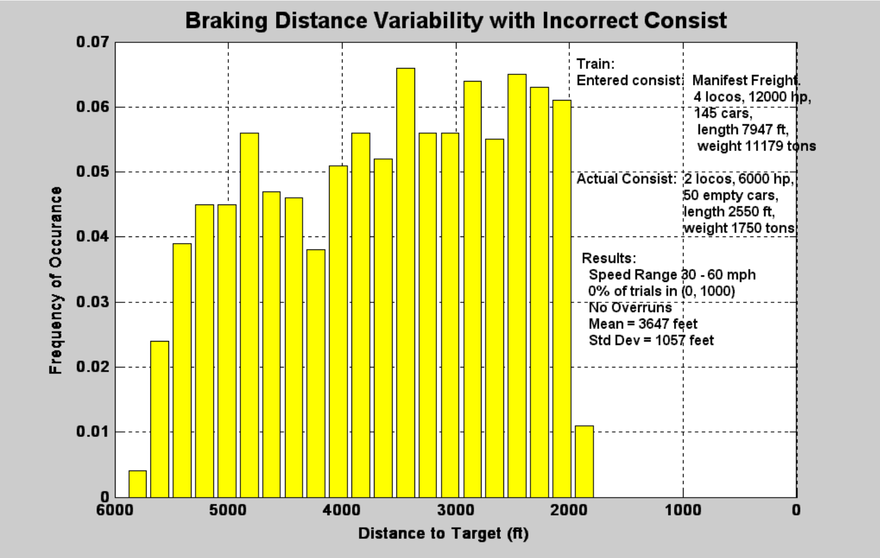


Figure 10. With Worst-Case Consist Assumptions, No Overruns Occur, But a 30–60 mph Train Never Stops within 1,000 ft of the Target

The braking situation improves when a freight train transitions to Confirmed Consist mode but it would still impact productivity. This is apparent from Figure 11, which shows that 21 percent of the time PTC would stop a train operating at 10 to 30 mph more than 500 feet from the target using Confirmed Consist mode assumptions for the braking algorithm. Figure 12 shows that 62 percent of the time PTC would stop a train operating at 30 to 60 mph more than 1,000 feet from the target using Confirmed Consist assumptions for the braking algorithm.

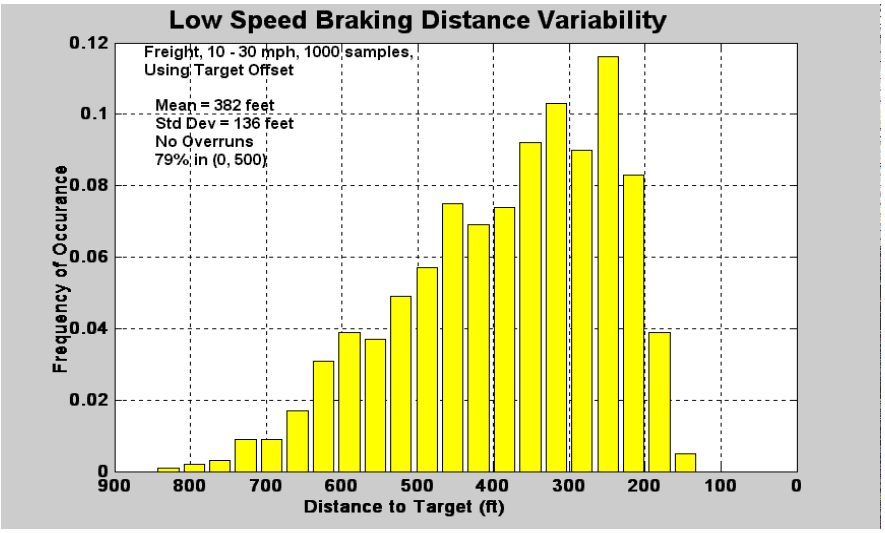


Figure 11. With Confirmed-Consist Assumptions, No Overruns Occur, But a 10–30-mph Train Stops within 500 ft of the Target only 79% of the Time

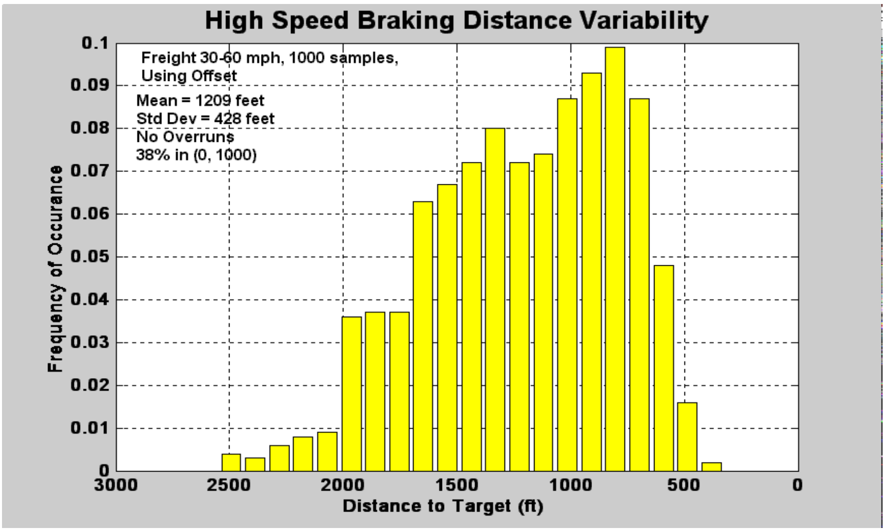


Figure 12. With Confirmed-Consist Assumptions, No Overruns Occur, But a 30-60 mph Train Stops within 1,000 ft of the Target only 38% of the Time

Because of the significant negative impacts such conservative PTC braking algorithms would have on railroad operations and because this problem is universal to all PTC implementations to date, a separate project has been initiated under FRA sponsorship to develop a more accurate algorithm that would adapt by measuring the actual braking performance and related characteristics of each specific train.

4.3 Mobile Radio Communications

4.3.1 The Challenge

In a moving block architecture, a train's continued movement depends upon its receiving periodic movement authority updates as the track clears ahead. These movement authorities can be much shorter than conventional signal blocks, and therefore must be updated frequently, particularly in the case of trains following one another at moderate or high speed.

Because PTC is a CBTC system, train location messages are transmitted periodically via the radio communication system to the controlling PTC server. The server in turn transmits updated nonoverlapping movement authority messages to trains. In addition, numerous other types of messages are communicated among trains, wayside equipment, and the server. Figure 13 depicts key information flows within the PTC system. In addition, the PTC-specific data flows shown, some railroads share their train control data link with other applications such as code line and/or work order reporting. The NAJPTC line uses the train-control data link as the channel for conveying code line (CTC signal code) messages.

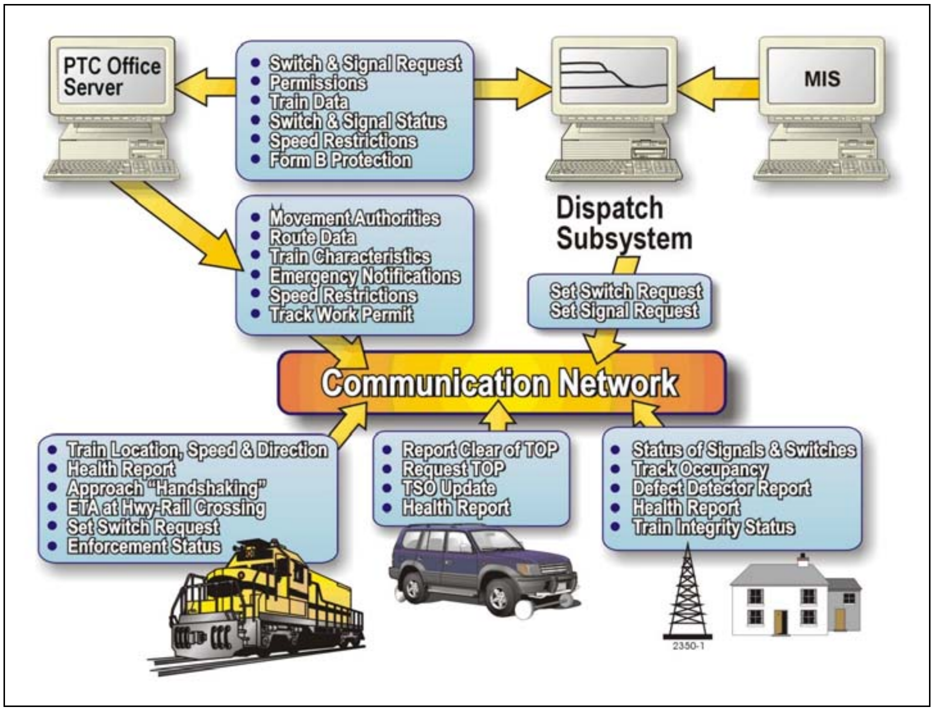


Figure 13. Key Information Flows in PTC (Note: In addition to the information messages shown, other messages such as heartbeats and acknowledgements can add appreciably to the volume of traffic.)

PTC uses an RF data link to communicate messages to and from trains. A limited amount of frequency spectrum is available to the railroads. Mobile RF data links incur dynamic signal degradation due to factors such as interference, thermal noise, contention, multipath and signal blockage. All of these factors limit the amount of data link throughput achievable as well as the message reliability and timeliness.

The primary ramification of insufficient communications system performance is a reduction in train throughput on the line, for the following reasons. Because of the communications-based architecture of PTC systems, message delays and limitations in train control data link throughput and message reliability can limit train throughput. The objective is for a train to receive its next movement authority update before it gets within braking distance plus warning time (distance) of the limit of its current authority. If the data link delivers a movement authority update too late, the associated train may have to reduce speed. If the data link does not deliver a movement authority update at all, the associated train will have to stop when it reaches the end of its last movement authority. If the data link fails to deliver train location updates, the server cannot advance the movement authority for a following train.

The greater the density and speed of trains under the coverage of any one data radio base station, the greater the data link throughput and message reliability requirements. The lower the message reliability, the greater the average communication delay, as the system must wait for message retransmissions. Also, the greater the update rate of location reports and movement authorities, the shorter the headway between trains (the closer they can get to the theoretical minimum spacing, which approaches the following train's braking distance). In addition, RF link loading is significantly increased by heartbeat messages. Heartbeats are messages sent frequently from all safety-critical nodes to indicate that they are still alive and can still be heard. Scenario-specific statistical analysis is required to quantify the above relationship between communication-system performances and PTC system performance.

4.3.2 Potential Solutions

The following are methods to increase the usable capacity and message reliability of an RF train-control data link.

- Increase data rate: This generally requires more bandwidth or higher order modulation. Frequency spectrum is precious, so more bandwidth may not be available. Practical limits exist on the order of modulation in mobile environments. The higher the order of modulation, generally the more sensitive is the data link to interference and distortion. Power amplifiers must be more linear (expensive). Also, channel equalization may be required. These factors can make the radios significantly more expensive. The increased sensitivity to noise means that co-channel transmitters will more severely reduce usable channel capacity in single frequency systems and more channels are required in frequency re-use systems (greater distance is required between base stations using the same frequency channel).

- Optimize protocol parameters: The performance of any communications protocol is highly dependent upon key protocol parameters, such as retransmission times and delay from the time a channel is sensed until transmission occurs in carrier sense multiple access (CSMA) or busy bit protocols. Optimization of these parameters for the specific train control application can significantly improve performance over default parameters. Selecting continuous transmit mode for busy bit base stations can appreciably reduce contention.

- Apply frequency reuse: Assigning different duplex frequency channel pairs to neighbor and next neighbor base stations, for example, allows continuous, simultaneous transmission and reception at all sites. The higher the required signal to noise ratio of the chosen modulation (as with higher order modulations), the farther away must be the nearest co-channel neighbor. When frequency re-use is used, the mobile units must have an algorithm for changing to the correct channel when handing off from one base station to the next.

- Obtain more channels: Often, high capacity is required at only a small percentage of locations. It may be possible to acquire more frequency channels in those areas without requiring the additional channels elsewhere.

- Eliminate link access contention: The RF data link in bound to a base station typically involves multiple trains contending for the same channel. Contention-based link access protocols (LAP) do not permit efficient use of available channel capacity. For example, the Aloha protocol has a theoretical maximum of 17 percent channel throughput (considerably less in most practical applications) and Slotted Aloha has a theoretical maximum channel throughput of 35 percent. CSMA and busy bit (CSMA's duplex equivalent) LAPs can perform better, but factors such as hidden terminals can limit CSMA performance on RF links. Noncontinuous base station transmission is typically used and can limit Busy Bit performance. Elimination of contention can significantly increase efficiency of channel utilization. Polling is a simple method of eliminating contention. However, polling wastes bandwidth because of guard times required when there is uncertainty in the communication delays, which is often the case with mobile users. Time division multiple access (TDMA) can permit nearly 100-percent channel utilization, but it is more complex to manage and the degree of efficiency is dependent upon the predictability of the message traffic patterns. TDMA often requires synchronization of application and communication frames to achieve optimum performance. Commercial off-the-shelf (COTS) or COTS-derived solutions are generally preferred for train-control applications since development of a new data link and/or protocol can be very expensive and time consuming. COTS solutions also offer the opportunity to benefit from economies of scale. However, COTS solutions do not generally accommodate application-specific features, such as frame synchronization.

4.3.3 NAJPTC Approach and Rationale

The U.S. railroad industry has six ultra-high frequency pairs with 12.5 kHz channel spacing assigned for train-control use. The protocol standard for use on these train control channels is of 1980's vintage and is known as Advanced Train Control System (ATCS) Specification 200 (Spec-200, now known as AAR Std. S-5800). The Spec-200 standard has a user data rate of 4,800 bits per second with a busy-bit contention protocol (duplex equivalent of CSMA). The ATCS protocol includes several priority levels, which are very important to avoid delaying time and safety critical messages in queues behind less critical messages. It also provides different types of service including datagram and reliable message delivery.

Initial analysis and requirements indicated that the current ATCS standard operating on a single channel pair in noncontinuous base station transmit mode could barely meet the needs of the PTC corridor in Illinois because of the low density of train traffic on that line. Because of this and for interoperability reasons, Spec-200 was the type of RF data link selected for the NAJPTC project. However, evolving requirements made the ATCS-200 data radio system's throughput insufficient for NAJPTC's needs. This included the requirement (identified later in the project) that the system fail safe within 20 s after a critical wayside device ahead of the train failed or could no longer be heard from. Meeting this requirement required a high rate of heartbeat messages that well exceeded the capacity of Spec-200 radios.

With the higher rate of heartbeat messages to accommodate a 20-second fail-safe response time, the following peak levels of RF data link loading were computed for NAJPTC scenarios. The peak demand data was obtained from the FRA-sponsored high-performance data radio project.

Scenario:	Peak Demand (approximate):
1. High Density Crossings	2,400 bps
2. High Speed Moving Block	6,400 bps
3. Multiple Meet/Pass	6,400 bps
4. Triple-Track High Density	15,864 bps

These peak-demand levels (which include Spec-200 upper-layer protocol overhead) significantly exceed the throughput capacity of Spec-200 data link inbound channel, which is approximately 1/10 of the 4,800 bps channel rate (480 bps) when operated at the required message first try success rate of 0.9 to 0.95 when contention, bit errors, multipath, and overhead are taken into consideration. The triple-track, high-density scenario could not occur on the NAJPTC line, but is shown here for purposes of extrapolation to a worst-case scenario in other potential territories.

Route integrity data (predominantly heartbeats from wayside devices) accounts for 38-58 percent of the demand in Scenarios 1-3 and 71 percent of the demand in Scenario 4. This data may not be required in some nonvital PTC implementations. Advance activation of highway crossings (not included in some PTC systems) accounts for 7–20 percent of the demand in Scenarios 1–3. It was not included in Scenario 4.

Possible solutions considered specifically for the NAJPTC line were as follows:

- Continuous transmit mode (achievable with existing Spec-200 equipment),
- Frequency reuse (achievable with existing Spec-200 equipment),
- Additional channels (may require modifying ATCS RF synthesizer),
- Change to a noncontention protocol (polling or TDMA) but maintain other ATCS characteristics, and
- Increase data rate by changing to quadrature phase shift keying or other modulation of similar order and efficiency while maintaining other ATCS protocol characteristics.

It was concluded that a higher performance data radio is needed. A project has been initiated under alternate funding to specify the requirements to develop and test a new generation interoperable data radio system suitable for PTC.

5.0 Lessons Learned

Besides the specific technical issue and lessons discussed in the previous section, the following are descriptions of other lessons learned from the NAJPTC project.

- Communications requirements: It is very important for the communications system design to take into account the communications demand (load) as a function of time and the impacts of latency and lost messages upon overall PTC system performance.

  The train throughput capacity of a PTC system is proportional to its data radio throughput capacity, which is determined by its link access protocol, channel rate, and other characteristics of the inbound radio link. The system design cannot be predicated upon a failure-free, first-time message success rate.

  For example, when a location report message does not get through the first time, it must be resent after some delay. This causes a variable message latency that will force a following train to operate further behind a preceding train than is achievable in an ideal implementation. This will be highly dependent on the first-time message success rate—a communication system with a 95-percent success rate will permit shorter average headways than a system with a 90-percent success rate, all else being equal.

  The overhead required for a closed-loop system associated with heartbeats and message acknowledgements required for ensuring that vital messages are not missed needs to be considered in the specifications. This is particularly important to ensure safety when some form of movement restriction must be subsequently applied within or to an already-issued authority.
  Since moderate and long-range mobile radio links (the type required for line of road communications) are generally very bandwidth-limited, every effort must be made throughout the development phase to minimize the size and rate of high priority messages transmitted over the RF data link.
- Message sequencing: Even when the system is operating properly, because of the nature of data radio communications, some messages may be lost and need to be retransmitted. Consequently, messages will sometimes be received in a different order than that in which they were generated.

  As a critical example, an NAJPTC system requirement was to withdraw an authority when a controlled signal goes to “stop” if the train has not already reached that point. But if the message reporting the signal change reaches the office segment before the train location report, the authority may be withdrawn in error. To solve this issue (which is common to all PTC systems operating in track circuited territory and was referred to as the “train-past-signal” issue), it is recommended to have the decision—as to whether or not a train caused the nearby signal to go red—be made on board by that train, because it alone has continuously available, current train location data.

A related problem experienced on the NAJPTC project was that of correlating location information from a variety of sources, especially when discrepancies were among the reports or communication delays were incurred on reports from some sources but not from others. Communicating trains, for example, reported their location to the server as determined by their onboard LDS units. In addition, the server received location-related information on the same trains from "on-sheet" (OS) circuits (which reported quickly, only incurring communication delays) and from intermediate track circuits (which had greater delay variations due to coded track circuits in addition to communication delays). Furthermore, both ends of each intermediate track circuit reported on the same intermediate track circuit independently of one another.

The numerous sources of location-related information (and delays in reporting that information) leave system designers with the dilemma of having to choose whether the system should immediately assume a train has moved to a new location on the basis of a single report from whichever sensor reports first, or wait until reports have been received from all relevant sensors, or something in between. Requiring the most conservative response (from a safety perspective) is not necessarily the best solution in cases where it only achieves safety overkill at the expense of excessive train delays.

Certain PTC objectives or functions are best satisfied by one assumption, whereas others favor a different assumption. The issue of message delivery with latency that varies must be considered in the design and provisions need to be made to accommodate messages from different sources being delivered with unpredictable sequences.

- Braking algorithms: An issue with the braking algorithms used was the conservatism required in the enforcement algorithms. NAJPTC was designed to feature positive enforcement of authority and speed limits to provide for added safety.

  Predictive braking accuracy is particularly important when a railroad wants to increase the capacity of a route using moving-block train control in which closer spacing of trains is the objective. The problem with trying to calculate the braking distance for a full-service application for enforcement purposes is that many braking variables are simply not known or only known to an approximation. These include brake valve type, brake-rigging efficiency, brake shoe composition, piston travel, and actual train weight. An additional problem is the inability to predict whether an engineer will use dynamic braking and whether or not the independent (locomotive) brake will be bailed. This uncertainty leads to further conservatism in braking algorithms.

  Braking algorithms are required to be robust enough that only a miniscule probability occurs for allowing a train to get past an authority limit, and therefore they must take into account the probability of bad braking characteristics. This is done by adding margin to the braking algorithm, which must also account for front and rear of train location uncertainties.

The warning associated with a conservative braking algorithm may cause locomotive engineers to operate their trains more conservatively than they otherwise would, based on their knowledge of train's braking characteristics (see the prior discussion on consist determination and verification for more details and potential solutions). A thorough statistical analysis should be performed to ensure that the probability of a train getting past its authority limit is not specified with excessive conservatism. This can have drastic effects on system feasibility.

- COTS safety case: Developing a safety case for the use of COTS hardware and software in a vital system was very challenging and not completely solved on the NAJPTC project. Most importantly, the system developer and safety assessors had limited insight into the internal design of COTS components to allow safety verification and validation. In addition, the project dealt with differences in interpretation of the FRA's new rule (i.e., the FRA's "Standards for Development and Use of Processor Based Signal and Train Control Systems," 49 CFR 236 Subpart H issued in 2005), because NAJPTC was the first vital train control system to fall under its regulation.

  Aside from these challenges, COTS promises a number of potential benefits in the design of a vital train-control system such as NAJPTC. These include reduced cost and schedule for system development, improved reliability and maintainability, state-of-the-art components and development tools, availability, and ease of incorporating product improvements. It is worth noting, however, that not all of these benefits may necessarily materialize for vital train-control applications because of the extra measures and mitigations required to attain the very high level of safety integrity required.

- Vital tracking of noncommunicating trains: The particular architecture selected for the NAJPTC project required vital tracking of noncommunicating trains, via track circuits and assignment of PTC authorities to noncommunicating trains (as well as communicating trains). This requirement was not fully solved, and it is highly recommended that an alternative architecture be developed that does not require vital tracking of noncommunicating trains via track circuits. Or, perhaps a solution might be devised that can tolerate more coarse tracking of noncommunicating trains.

  A possible alternative solution/migration path for a line equipped with CTC would be to progressively equip trains with PTC and have it operate transparently in the background without the ability for displaying authorities. Trains would operate according to wayside signals and regular bulletins. Authority limits and bulletin restrictions would be transmitted to the train for enforcement purposes, and trains would be provided with a locomotive display for the purpose of entering required data and for providing warnings of speed violations.

Under this migration path, communicating trains would be fully protected against other communicating trains. Partial protection against noncommunicating trains might be gained by applying a railroad-configurable speed restriction on communicating trains approaching a point of potential convergence with a noncommunicating train. Safety would be enhanced as more and more locomotives became equipped. When enough locomotives became equipped to warrant the removal of the signal system (or intermediate signals), the system could then permit the display of authorities and restrictions. This transition could be facilitated through functional negotiation or through upgrading of the onboard system.

The key advantage of this migration path is that it would avoid the costly step of installing PTC equipment (e.g., wayside interface units (WIU)) at intermediate signal/track circuit locations only to have them eventually discarded upon transition to standalone PTC mode.

- Train control design philosophy when using two fail-safe systems: One of the problems encountered in the NAJPTC project occurred when one of two fail-safe devices that measured the same condition (track occupancy) failed. The design philosophy was to assume the worst-case condition; namely, that the track was occupied, even though the other fail-safe device was measuring no occupancy. This led to incorrect conclusions about the location of unequipped trains on more than an acceptable number of occasions.

  A better design philosophy would have been to accept the less restrictive condition of the two fail-safe devices measuring the same condition. This will reflect the actual condition more accurately than using the worst-case condition. Because both devices were fail-safe, no unsafe condition should result from this less restrictive approach. In the case of the NAJPTC project, this approach would have avoided incorrect conclusions about the location of trains as only real occupancies would have been reported as occupancies.

- Incremental development: The NAJPTC project was one of the most complex system development/integration projects undertaken to date. The project was to develop a complex, highly distributed system that included mobile nodes and was required to meet stringent safety, availability, and performance requirements. The requirements for NAJPTC far exceeded those of any train-control system previously implemented.

  The original plan called for seven builds, which was probably the minimum number of builds feasible for a project of this magnitude. Unfortunately, the required schedule for project completion was too short to accommodate seven builds, so the number of builds was reduced, but the total functionality was not. This resulted in the complexity of the second build becoming so high that it proved to be unachievable in a single build.

So, the greatest lesson illustrated by the NAJPTC project was that such large systems must be developed incrementally. This relates to the lessons discussed later regarding visible and quantifiable progress, sequence of development, and no short-cuts.

- Thorough specifications: To develop PTC systems requires much more railroad operational knowledge than required for the signal systems they replace, knowledge that not every system developer may have. Therefore, procurement specifications must be extremely thorough, unambiguous, understandable at all levels, and correct. System engineers well trained in effective specification writing and experienced with railroad operations and control system technologies are necessary to generate such specifications.

  It is also useful to prepare a concept of operations that mirrors the specifications in language appropriate for a nonexpert to provide insight as to why the system specification says, "The system shall do this. . . . ."

- Knowledge transfer: It is necessary for the system developer to understand the rationale behind the specifications; i.e., why each requirement is there and the associated underlying train operations. This should begin with a thorough meeting soon after (or preferably before) the system development contract is signed so that domain knowledge is transferred early.

  If the design engineers are not familiar with railway operations, they need to spend time on the railway with operating officers to gain domain knowledge.

- Teamwork: A cooperative working relationship between the customer and the system developer is essential to obtaining a good product on time and within budget. An adversarial relationship stifles communication and knowledge transfer, which increases cost, extends project implementation time, and undermines confidence in the system.

- Meetings: Although telephone conference calls and e-mails are useful for routine communications, face-to-face meetings can be better for problem solving and for exchange of critical information. When face-to-face meetings are not practical, use of an Internet document review tool is recommended so all parties can review and discuss the same document page simultaneously.

  Most important, however, is that all decisions, agreements, and conclusions be clearly documented in detail and preserved for future reference. E-mail can be beneficial in this regard.

- Early test planning: The test plan should be developed for use by designers early in the project, before the design is finalized, to assure that the system design is comprehensive. This test plan may take the form of a requirements verification conditions and criteria matrix (RVCCM).

The RVCCM includes a list of each system requirement to be tested, the operational conditions under which it will be exercised and its acceptance criteria. The RVCCM also indicates whether each test is to be performed in the lab and/or field. The RVCCM provides a different perspective from the system specification that is invaluable in correctly interpreting each requirement.

- Sequence of development: In large programs with tight implementation schedules, it is imperative that the normal development sequence is not short-cut. Coding should not start before the implications of the requirements are fully understood, and before the design is solidified and agreed to.

  Coding before significant design issues are resolved is a recipe for design rework later with resulting cost and schedule overruns.

- No short-cuts: Developing a new PTC system is a large undertaking, particularly if it is to be a standalone (vital) system. There are numerous facets and variations to typical train moves, each one of which must be accommodated by a PTC system.

  Customers must have patience and should be cautious regarding any proposed quick, inexpensive development solution that does not specifically address details and difficult technical performance and safety issues, such as those discussed.

  Developers must have PTC development experience to understand the complexities involved and how to adequately address them.

- Test environment: Even with careful planning and coordination to permit system testing on an active rail line, NAJPTC field testing proved to be very time consuming and expensive. Test train movements could not interfere with revenue trains. This often resulted in the test train and all associated test personnel waiting for a window in which to operate between revenue trains.

  Changes in test plans resulted from encountering unexpected events in the field. Railroads and regulatory agencies required that extensive documentation be generated upon any change in test plans.

  Coordinating among the schedules of numerous participants from the railroads involved, FRA, state agencies, suppliers, the NAJPTC project's Program Office (i.e., TTCI), and its system engineer The NAJPTC project's system engineer was extremely difficult and left virtually no flexibility to accommodate unexpected events.

  Test operation at high speeds required significant additional precautions, such as flagging personnel at highway-grade crossings and absolute block protection around the test train.

Compounding the issue of testing in a revenue track environment was the approximate one year lead time it took to implement any change to the WIU software (which involved making the change, verifying it in the lab, in the field, and by an independent auditor, rolling it out to all sites in the affected territory, and then field-verifying it). This was because the WIUs were part of the vital revenue signaling system on the line.

These considerations added significantly to the time and expense incurred with field testing. A controlled PTC test bed on a dedicated test track (absent of revenue trains and standard railroad regulatory requirements) could have benefited the NAJPTC project by avoiding or reducing the above issues.

- Shadow mode testing: Shadow mode testing placed the NAJPTC system in daily operation on select revenue-service locomotives without a brake interface and without any driver display or input. The system operated in the background with logging occurring in the office and in the onboard computer. This permitted considerably more scenarios to be exercised at substantially less cost than was possible in manned field testing.

  Shadow mode testing was geared towards wringing out problems associated with the vital tracking of noncommunicating trains, integrating the tracking of fitted trains using LDS and track circuit information, and the association of authorities to trains.

  Shadow mode testing provided a tremendous boost in the amount of information available to use in solving problems, especially those that only appeared outside the lab. Unfortunately, it was not available until late in the project.

- Visible and quantifiable progress: A key to ensuring the successful conclusion of a complex system is to show visible progress throughout a relatively long development process. This not only provides a tangible means by which to measure progress, but also allows users to gain experience with parts of the system and to provide feedback into subsequent development stages. This implies implementing, testing, and demonstrating useful interim releases of the system that provide ever-increasing levels of functionality.

  A quantitative means of monitoring and demonstrating progress that proved very useful was the implementation of metrics or technical performance measures (TPM). TPMs that proved to be most useful on the NAJPTC project, particularly during shadow mode testing, were as follows:

  - PTC officer server (POS) failures per 24-hour POS operating hours for all trains (plotted by week and as a rolling average)

- False nonexplicit modes per 24-hour POS operating hours for all trains (plotted by week and as a rolling average); nonexplicit is a degraded operating mode that the POS has entered during which no new or extended authorities will be issued because it has detected a discrepancy between its status and that of CAD.
- False nonexplicit modes per 24-hour POS operating hours for communicating trains only (plotted by week and as a rolling average)
- False nonexplicit modes per 24-hour POS operating hours for non-communicating trains only (plotted by week and as a rolling average)
- False reports of authority violations per 100 train miles for all trains (plotted by week and as a rolling average)
- False reports of authority violations per 100 train miles for communicating trains only (plotted by week and as a rolling average)
- False reports of authority violations per 100 train miles for noncommunicating trains only (plotted by week and as a rolling average)
- False reports of enforcements per 100 train miles for communicating trains (plotted by week and as a rolling average)

The TPMs were updated and reviewed among the project team weekly and presented to stakeholders monthly (see Figures 14 and 15). This provided an objective and quantitative means of measuring progress in solving system performance problems.

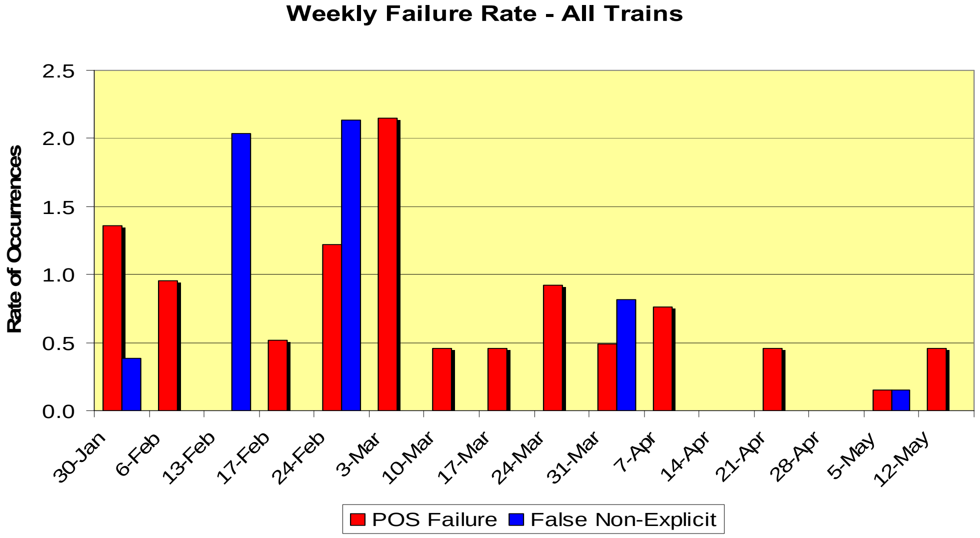


Figure 14. Example of TPM for POS Failures and Nonexplicit Mode Events

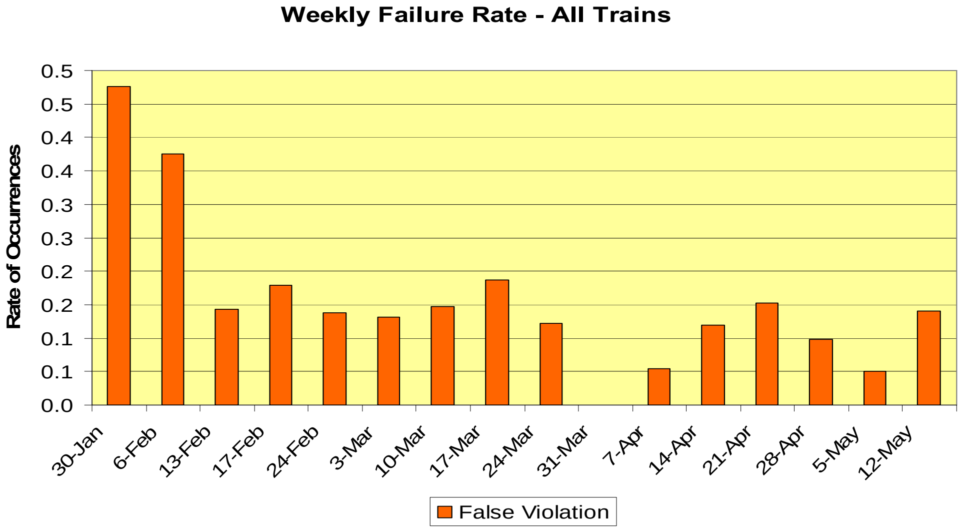


Figure 15. Example TPM for False Reports of Authority Violation

- System Performance: In developing software-intensive systems, often the tendency is to focus only on functionality and interfaces, largely ignoring the performance aspects.

  In the development of real-time control systems, performance issues can be complex and must not be neglected or postponed, especially for those systems having RF communications in the loop. Of particular importance is the relationship between RF communications system bandwidth, message latency, message reliability, system-response time to changes in safety conditions, and train throughput capacity on the PTC corridor.

  Designing for safety and interoperability can adversely affect system performance, if performance is not concurrently factored into the design. A PTC system with poor performance (e.g., excessive false enforcements or increased headways) will not be acceptable.

  To understand complex technical performance issues and to develop an efficient, coordinated/balanced total-system solution, it is strongly advisable for the development team to heavily involve at least one system engineer with expertise in all of the key areas (RF communications, network protocols, real-time control systems, safety, and train control) throughout the project.

  The bottom line is that the design team must address functionality, performance, and safety concurrently and integrally.

6.0 Conclusions

PTC offers the promise of significant potential benefits in railroad safety, capacity, and efficiency. However, PTC reveals a different and much more complex but not insurmountable set of design issues than those encountered with traditional train-control approaches. Like many railroading problems, the issues associated with train control are very scenario-dependent and the solutions must be engineered accordingly. Much more so than traditional signaling design, PTC development requires a solid understanding of railroad operating rules, because it embodies many of them. Finding the optimum solutions to these challenges often requires well-coordinated customer and developer trade analyses of potential cost and operational ramifications.

This report has identified key issues encountered on the NAJPTC project along with potential and chosen solutions, as well as the rationale for those choices. The experiences gained from this project have benefited other PTC developments and have led to the inception of subsequent projects to further address issues identified on this project.

Appendix A.

NAJPTC Onboard Equipment

Figure A-1 shows the installation of the NAJPTC display in a freight locomotive.

Figure A-1. NAJPTC Display Installed in a P42 Passenger Locomotive

Figure A-2 illustrates the following primary elements of the NAJPTC display.

1. Mode indicator: Continuously visible indicator providing maintenance and operational mode indication (e.g., power up, initializing PTC, active PTC)

2. Speed and location: Continuously visible indicator providing textual speed and milepost location data.

3. Speed limit graphic: Represents the most restrictive speed limit for a prescribed area in the display horizon. A text box reinforces the speed limit and is located within the graphic. The text box will also be used to indicate whether the area is a restrictive speed restriction and will contain the text "restrictive" as required.

4. Vertical speed scale: The speed scale is a linear scale that provides a constant-speed value scale which will adjust vertically in conjunction with the train speed pointer to encompass the full range of possible train speeds within a limited

vertical window area. The speed scale also provides a reference for speed limit restrictions in the display horizon.

5. Train speed pointer: The train speed pointer provides a graphical representation of the train's speed using the speed scale as well as a change in vertical height as the train accelerates and decelerates. The vertical distance between the speed pointer and upcoming speed-limit graphics provides a comparative relationship between the train's speed and the upcoming speed limits. The train pointer remains stationary in the horizontal location and extends down into the bottom auxiliary area and into the train position and length indication.

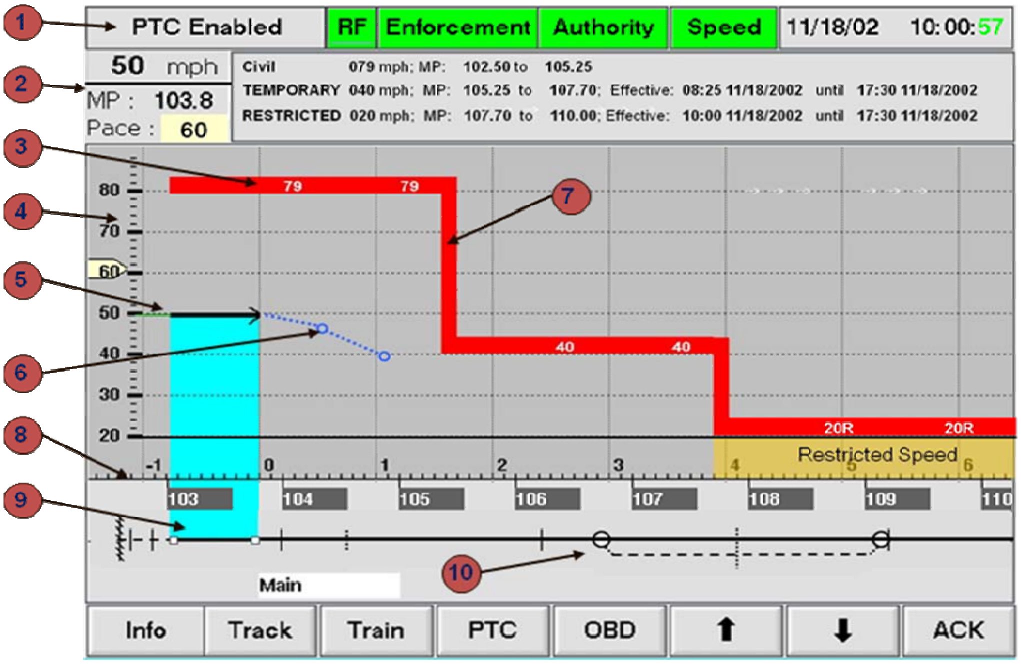
6. Speed prediction indicator: A graphical vector with two filled-in circles representing the train's predicted speed and location in 30 s and 60 s, respectively. The upward and downward direction of the vector represents if the train is predicted to accelerate or decelerate, respectively.

7. Speed change or authority limit bar: This vertical bar represents a change in speed or end of a train's authority to move (speed = 0). The bottom of this bar contains a graphical hint of the lower speed limit if it is currently off the scale with respect to the train's current speed.

8. Train location scale: The train location scale is a linear scale that provides an absolute reverence of the location of graphical entities (track profile data, speed limit boundaries, speed prediction indication, and work limit) with respect to the front (point movement) of the train. The scale is fixed and has major scale marks in miles and minor scale marks of 2/10ths of a mile. The scale extends at least 6 mi in the front of forward motion of the train and at least 1/4 mi from the rear of forward motion of the train.

9. Train Position and Length Indicator: This indicator is connected to the train speed pointer and varies in horizontal length, which represents the length of the train. The length measurement is relative to the train location scale. The position of the train with respect to track profile icons can be determined from the train location scale.

10. Track profile indicators: Track profile indicators consist of mileposts, crossings, control points, hot box, and defect detectors. Track profile indicators move along the horizontal and relative to the speed of the train.



Civil 079 mph; MP: 102.50 to 105.25
TEMPORARY 040 mph; MP: 105.25 to 107.70; Effective: 08:25 11/18/2002 until 17:30 11/18/2002
RESTRICTED 020 mph; MP: 107.70 to 110.00; Effective: 10:00 11/18/2002 until 17:30 11/18/2002

Figure A-2. Primary Elements of the NAJPTC Display

Figures A-3, A-4, and A-5 show remaining NAJPTC onboard hardware items installed on a locomotive.

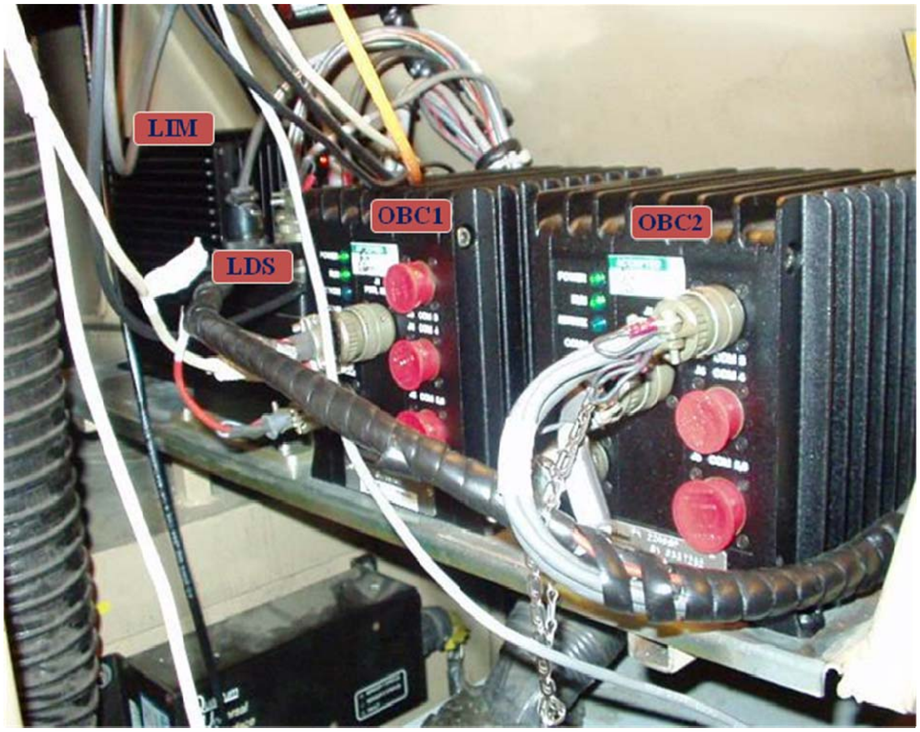


Figure A-3. Locomotive Interface Module, Location Determination System, Onboard Computers

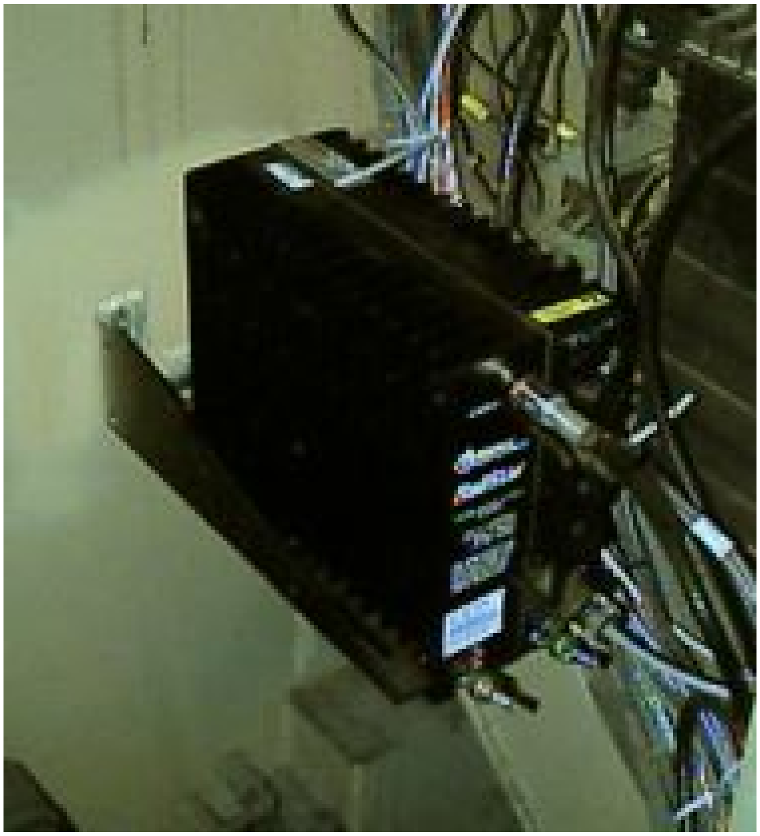


Figure A-4. Onboard Mobile Communications Package

Figure A-5. Onboard Antennas

NAJPTC Wayside Equipment

Figures A-6, A-7, A-8, and A-9 show a typical WIC installation. The primary components are a Microlok electronics cabinet, an ATCS Specification-200 Mobile Communications Package (MCP), and antennas for the MCP and global positioning sensor.

Figure A-6. Typical WIU Housing

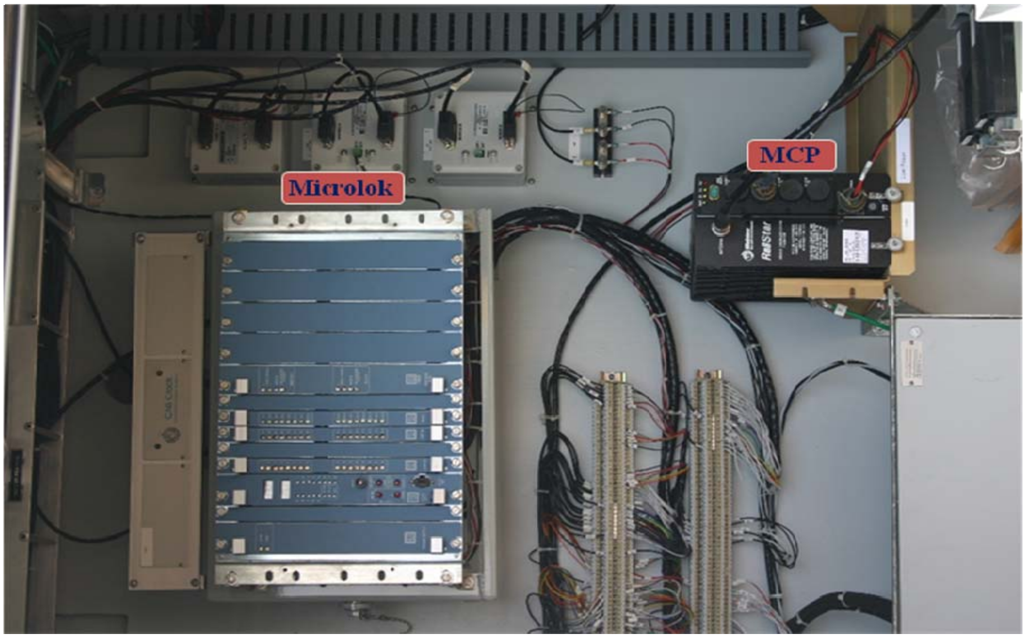


Figure A-7. Typical Microlok and MCP Installation in WIU Housing

Figure A-8. Typical GPS Antenna Installation on WIU Housing

Figure A-9. MCP Antenna Outside WIU Housing

NAJPTC Office Equipment

Key office equipment elements are the quad-redundant POS shown in Figure A-10 and a remote terminal shown in Figure A-11.

Figure A-10. NAJPTC POS

Figure A-11. POS Remote Terminal

Appendix B.

Status of NAJPTC Implementation by Function

The NAJPTC project was terminated during the Build 2 phase. At the time of project termination, all Build 1 functionality and much of the Build 2 functionality had been implemented and successfully tested. Table B-1 provides the status of each function at the time of project termination. The status of each function is defined in the following terms:

w	working (tested & demonstrated)
pw	partially working
nw	not working
nt	not tested.

Table B-1. NAJPTC Build 1 and 2 Functions			STATUS
System			
	Start-up		
		Verify health of all components (Server, Communications, Onboard computers (OBC), WIUs)	w
		Verify correct software version of OBCs WIUs (Software Version Control)	w
	Ongoing		
		Monitor health of all components (Health Monitoring & Diagnostics)	w
	Shut down vital component if failure detected		w
	Time Synchronization		w
	System Response to failed OBCs		w
	System Response to failed WIUs		pw
Location Management			
	Train Initialization		
		Acquisition/Verification of Route Data	w
		Acquisition of consist data	w
		Acquisition of bulletin data	w
		Departure Test	w
	Onboard Location Tracking		w

	Track Resolution		
		Semi-automated at start-up	w
		Automatic standalone tracking through switches	w
	Onboard Display of Train Location		w
	Onboard Display of Train Speed		w
	Onboard Display of Track Profile and Characteristics		w
	Onboard Display of Route		w
	Server Location Tracking of Trains and Vehicles		
		Communicating Trains	pw
		Noncommunicating trains by track circuit	nw
	Reporting train location to CAD		
		Communicating	pw
		Noncommunicating	pw
	Remote train location reporting		
		Communicating	nt
	Train Termination of PTC functions		w
Authority Management			
	Authority Issuance		
		Signal-based	pw
		Forms-based (with written instructions)	pw
	Display Authority and Instructions - Text Format		w
	Display Authority and Instructions - Graphic Format		w
	Automatic Release of Authorities		w
	Authority Cancellation (by train dispatcher)		w
	Authority Modifications		w
	Authority Verification		
		Safety Check - verify safe to issue	pw
		Seek and verify acknowledgement from joint holders, if applicable	nt
		Ensure that authorities are not delivered to train before applicable bulletins	w
	Incremental Authorities - Moving Block for Communicating trains		pw
	Broken Rail Detection (unidentified track occupancy)		w
Speed Management			
	Deliver Civil Speed Limits to trains as required		w
	Temporary Speed Restrictions (TSR) (Form A or V)		
		Receive TSRs from CAD or other source	w
		Distribute TSRs to affected trains on initialization or when received	w
	Maintenance of Way Protections (MWPs) (Form B or W)		
		Receive MWPs from CAD or other source	w
		Distribute MWPs to affected trains on initialization or when received	w
	Advisories		
		Receive Advisories from CAD or other source	w

		Distribute Advisories to affected trains on initialization or when received	w
	Apply Lading/Equipment Speeds Restrictions as required		w
	Apply Speed Restrictions based on Route Integrity Monitoring		
		Restricted Speed (head end only) for track circuit anomaly, slide detected, etc.	w
		Stop & Inspect for potential open switch	nt
	Apply restriction at nonfunctional HRX or for extended activation		nt
	Onboard Display of Integrated Speed Limits and Restrictions		w
Train Integrity Monitoring			
	Train Intact/Cut Status		nt
	Detect Emergency Brake Application		nt
Route Integrity Monitoring			
	Monitor Track Occupancy by Signal Block		pw
	Monitor Signals		pw
	Monitor Power-Operated Switch Position and Control Point Occupancy		pw
	Monitor Hand-Operated Switches		pw
Crossing Monitoring and Activation			
	Activate Highway Rail Crossing Warning Devices		nt
	Monitor Health of HRI System		nt
Emergency Warnings			
	Emergency Brake Application Warnings		nt
	Authority Violation Warnings		nt
	Unauthorized Movement Warnings		w
Response to Emergency Warnings			
	Emergency Reduction of Authority or Application of Restricted Speed		nt
Warnings and Enforcement			
	Identify Enforcement Targets		
		Entry point to PTC	w
		Authority Limits	w
		S&I Restrictions	w
		MWP Limits	w
		Speed Limits and Restrictions	w
	Predictive Enforcement Warnings		
		Entry point to PTC	w
		Authority Limits	w
		S&I Restrictions	w
		MWP Limits	w
		Speed Limits and Restrictions	w

	Predictive Enforcement		
		Entry point to PTC	w
		Authority Limits	w
		S and I Restrictions	w
		MWP Limits	w
		Speed Limits and Restrictions	w
	Reactive Enforcement Warnings		
		Speed Limit Ceilings	w
		Restrictions imposed over train occupancy	nt
	Reactive Enforcement		
		Speed Limit Ceilings	w
		Restrictions imposed over train occupancy	nt
	Enable/Disable Enforcement		w
	Detect and Report Enforcement enable/disabled		nt
	Notification when enforcement is invoked		w
		Functions Required	
		Functions tested & demonstrated (**w**)	55
		Functions partially working (**pw**)	12
		Functions not working (**nw**)	1
		Functions not tested (**nt**)	14

Appendix C.

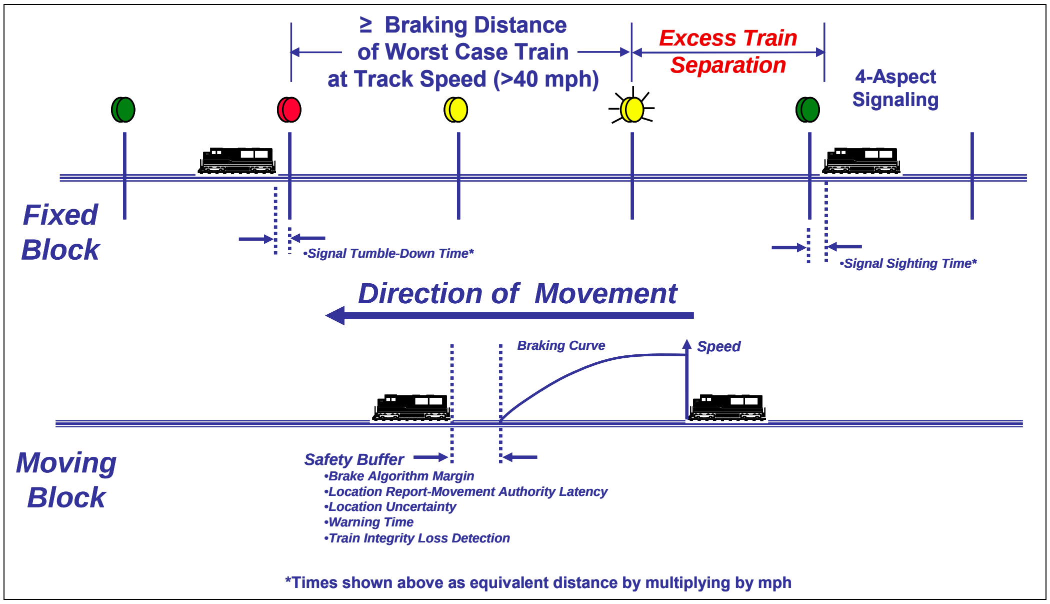
Quantification of Potential Increased Capacity and Reduced Headway with Vital, Moving Block PTC

Methodology

The potential headway reductions and capacity increases that could be gained by using a vital, moving block PTC system are analyzed and presented here. Trains were modeled operating in a following move scenario at the same speed (e.g., double track current-of-traffic, or fleeting on single track), with the results compared against a conventional 4-aspect signaling system. Because PTC Standalone mode was a Build 2B feature and Build 2B was not funded, the potential benefits of moving block have not been proven by actual implementation and field testing.

The simulation parameters and results are for the case of a 123-car loaded grain train powered by four SD-40 locomotives, traveling at prescribed speeds, considering various grades, block lengths, warning times, and brake algorithm margins.

The average train stopping distances (using a nominal full-service braking application) were obtained from TOES^{TM} simulations, whereas the rest of the parameters are from NAJPTC requirements, design capabilities, or typical railroad signaling system attributes. Every attempt has been made to make the predictions of PTC performance accurate by using actual NAJPTC system design parameters, braking algorithm margins, and nonidealities. Figure C-1 shows how these parameters relate to the scenarios.



*Times shown above as equivalent distance by multiplying by mph

Figure C-1. Relationship of Moving Block and Conventional Signaling Parameters Used in Analysis of Potential Headway Reduction and Capacity Increase

Unless otherwise noted, the results presented are for a pure moving block PTC system. As such, the models assume the use of a vital train integrity detection device (i.e., that track circuits are not required for train integrity protection). The NAJPTC Standalone Territory mode implementation also accommodated a hybrid moving block/fixed block mode of operation. The hybrid mode would use track circuits for train integrity protection, resulting in a speed restriction being enforced through an occupied block ahead. Results for the hybrid mode of operation are presented as well.

The characteristics of the conventional case modeled are:

- Both leading and following trains are operating at the same, constant, specified speed
- 4-aspect signaling with coded track circuits (signal tumble-down time considered). Aspects defined as:
  - Restricting—proceed at restricted speed.
  - Approach—proceed prepared to stop before any part of train or engine passes the next signal. Freight trains exceeding 30 mph must immediately reduce to 30 mph. Passenger trains exceeding 45 mph must immediately reduce to 45 mph.
  - Advance approach—proceed prepared to stop at second signal. Trains exceeding 40 mph must immediately reduce to 40 mph.
  - Clear—proceed.
- The 4-aspect signaling results in the following minimum train separations:
  - 3 blocks separation for train speeds above 40 mph;
  - 2 blocks separation for train speeds of 31–40 mph;
  - 1 block separation for train speeds of 21–30 mph;
  - Full-service braking distance separation for trains in same block with speeds ≤ 20 mph.

Analysis results are provided for trains traveling at 60, 40, and 30 mph.

Table C-1 shows the simulation parameters and results for the loaded grain train traveling 60 mph on a level route, using a block length of 2.5 miles, a 20-second warning time, and the NAJPTC brake algorithm margin.

Table C-1. Analysis of Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling Using 2.5-Mile Block Length for a Train Traveling 60 mph on a Level Route

Train Simulated: 123-car loaded grain train with 4 SD-40 locomotives		
Parameters Used in Analysis:		
Route		
0% grade		
Train		
Speed: 60 mph		
Length: 6,798 ft		
Weight: 14,088 tons		
Moving Block and 4-Aspect Fixed Block Signaling Parameters		
	feet	
3 block lengths	39,600	(2.5 miles/block)
+ signal tumble-down	1,584	(6 sec/block)
+ signal sighting time	704	(8 sec)
- average train stopping distance	7,531	(7,531 ft per TOES, using full-service braking)
- brake algorithm margin	1,762	(1,762 ft per NAJPTC braking algorithm)
- LR-MA latency[1]	1,320	(15 sec/LR)
- location uncertainty	10	(10 ft per NAJPTC System Specification requirement)
- warning time (to crew)	1,760	(20 sec)
- train integrity loss detection	1,760	(20 sec)
Potential Headway Reduction	**27,745 ft (or 315 seconds)**	
Potential Capacity Increase	**133% (factor of 2.33)**	
[1] LR-MA latency refers to the inverse of the movement authority update rate, which generally equates to the location report rate for the case of close following moves.		

Baseline Case, Running over Level Route

The following results (Figures C-2 through C-4) are for the baseline case in which the train is operating over a level route. The full-braking margin is used with a 20-second warning time to the engineer before enforcement. It is also assumed that a vital train integrity protection device is used, so that no enforced speed restriction is necessary through an occupied block ahead. Figure C-1 illustrates the simulation parameters.

Train Speed = 60 mph

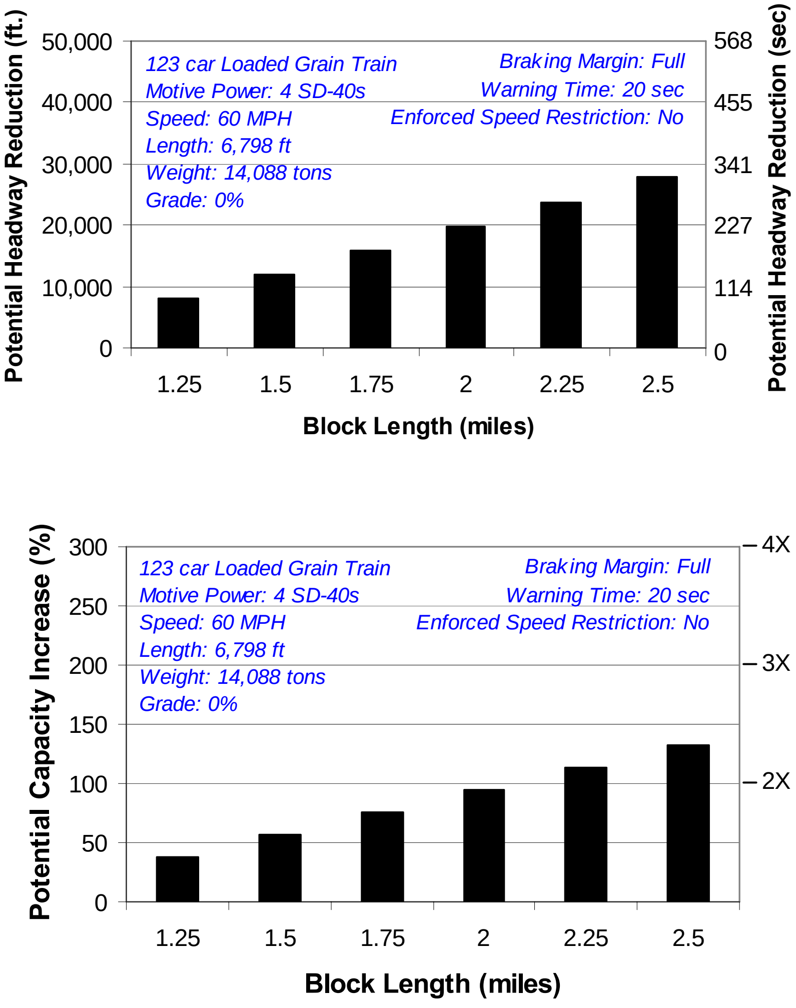
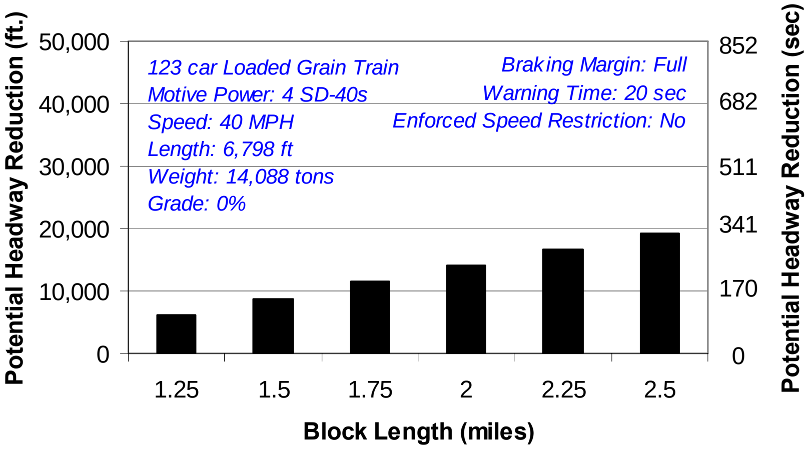


Figure C-2. Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling for a Train Traveling 60 mph on a Level Route, Using a 20-Second Warning

Train Speed = 40 mph



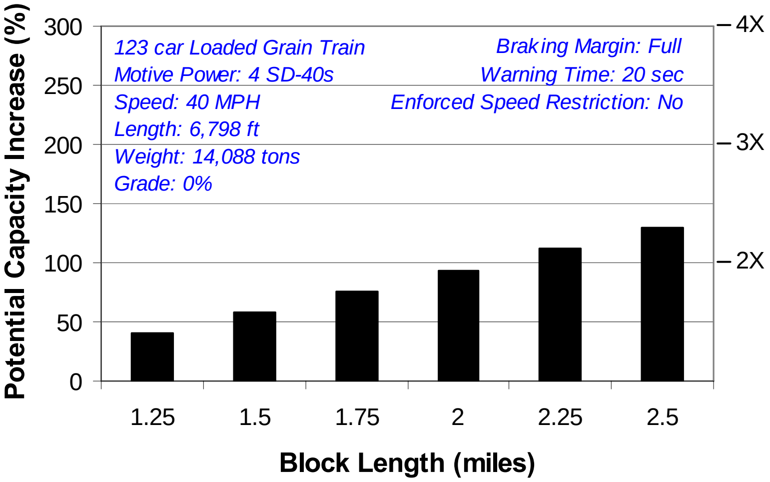
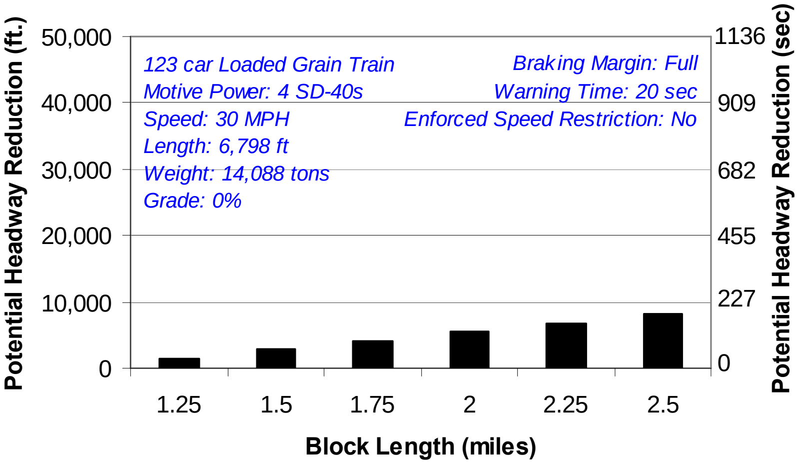


Figure C-3. Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling for a Train Traveling 40 mph on a Level Route, Using a 20-Second Warning

Train Speed = 30 mph



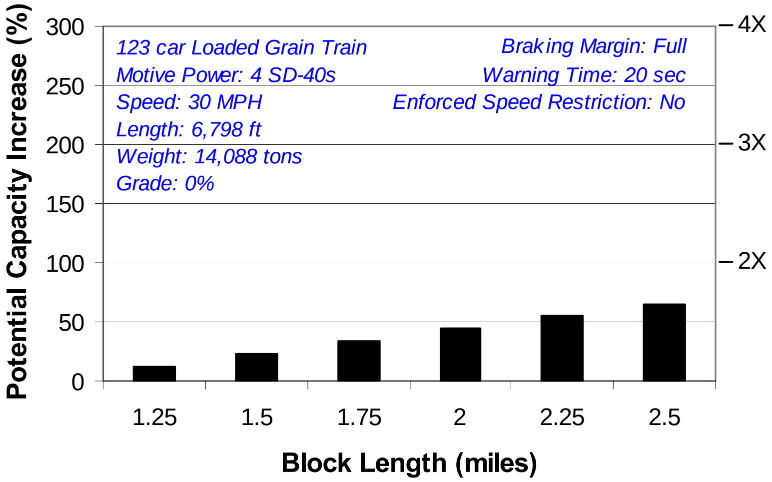
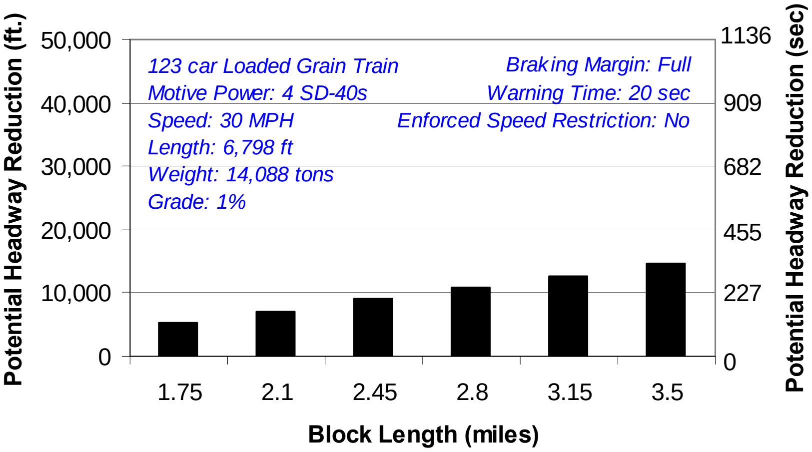


Figure C-4. Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling for a Train Traveling 30 mph on a Level Route, Using a 20-Second Warning

Baseline Case, Ascending a 1 Percent Grade

For trains traveling up a grade, the improvements in potential headway reduction and capacity increases become even more apparent. If the same train is analyzed traveling up a 1 percent grade at 30 mph, the potential headway reduction and capacity increases provided by the vital, moving block PTC system are as shown in Figure C-5. Note that in this case, the block lengths have been increased proportionately to account for the 1 percent grade, assuming the same signal locations are used for trains ascending and descending the grade.

Train Speed = 30 mph



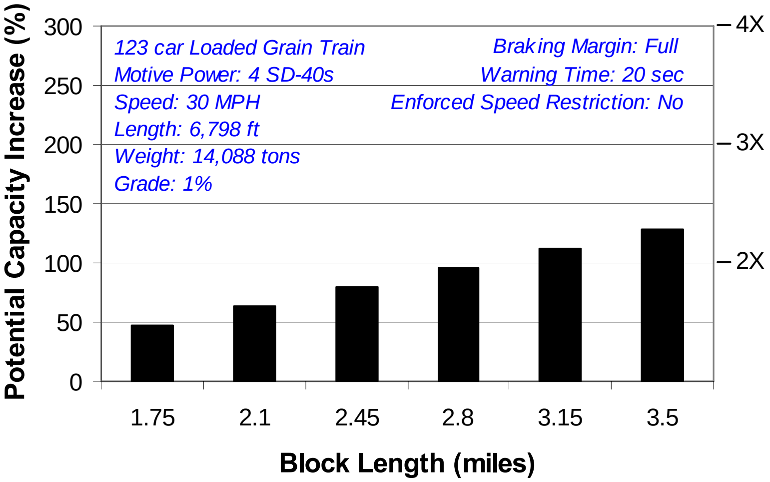


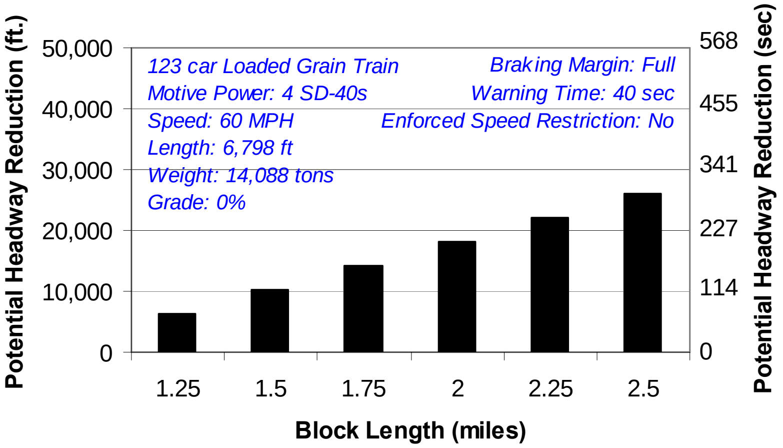
Figure C-5. Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling for a Train Traveling 30 mph up a 1% Grade, Using a 20-Second Warning

Increase Warning Time to Engineers before Penalty Enforcement

Increasing the enforcement warning time to engineers negatively impacts potential headway reduction and capacity increases. Returning to the scenario in which the train is traveling 60 mph on a level route and increasing the warning time to engineers from 20 seconds to 40 seconds, the resulting potential headway reduction and potential capacity increases are illustrated in Figure C-6. For a block length of 2.5 miles, the potential capacity increase has dropped from 133 percent to 115 percent compared to the case in which the warning time is 20 s.

The negative impacts in potential headway reduction and potential capacity increases (compared to the scenario with a 20-second warning) are due to the fact that the earlier engineers receive the warning that penalty braking enforcement is imminent, the more likely they are to brake the train sooner than is necessary to stop the train in time.

Warning Time = 40 Seconds



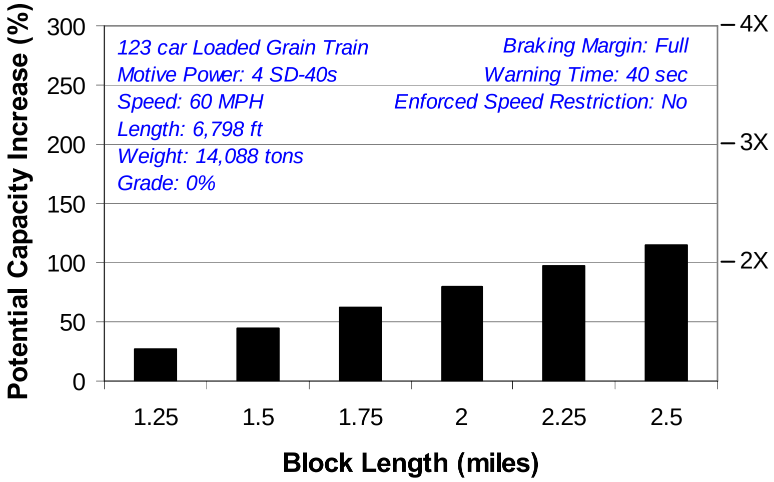


Figure C-6. Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling for a Train Traveling 60 mph on a Level Route, Using a 40-Second Warning

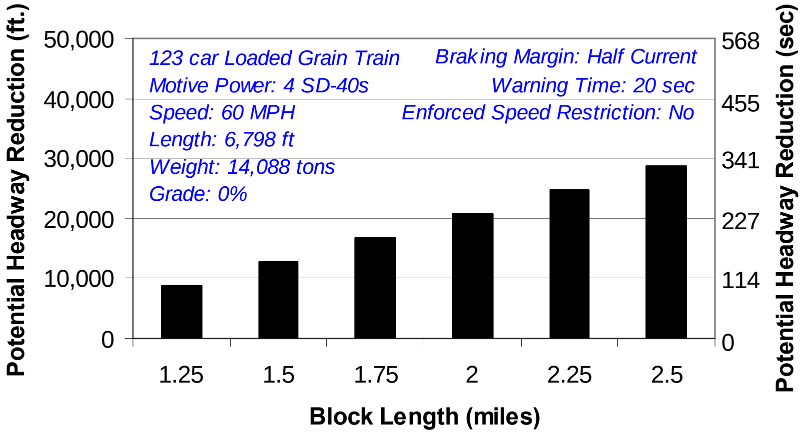
Reduce Braking Margin

One area in which PTC technology needs further research and development is in braking algorithms. The variability of performance within each train's braking system requires a braking margin or safety net to be added in to the predicted braking distance. If the PTC system would know the train's braking characteristics with greater accuracy, this margin could be reduced. For example, if the representative model's braking margin would be cut in half (from 1,762 ft to 881 ft), then the potential headway reductions and potential increases in capacity would improve as Figure C-7 shows. In this case, capacity could potentially increase by 10 percent when compared to the case in which the full-braking margin is used.

The theoretical performance limit (best case) for a PTC braking algorithm would eliminate the braking margin altogether. The potential headway reductions and potential increases in capacity would further improve, leading to the results seen in Figure C-8. In this scenario, capacity could potentially increase by 21 percent when compared to the case in which the full-braking margin is employed. It is not likely that this ideal case will ever be achieved.

An FRA-sponsored project has been initiated to develop a more accurate braking algorithm that will adapt by measuring the actual braking performance and related characteristics of each specific train.

Halved Braking Margin



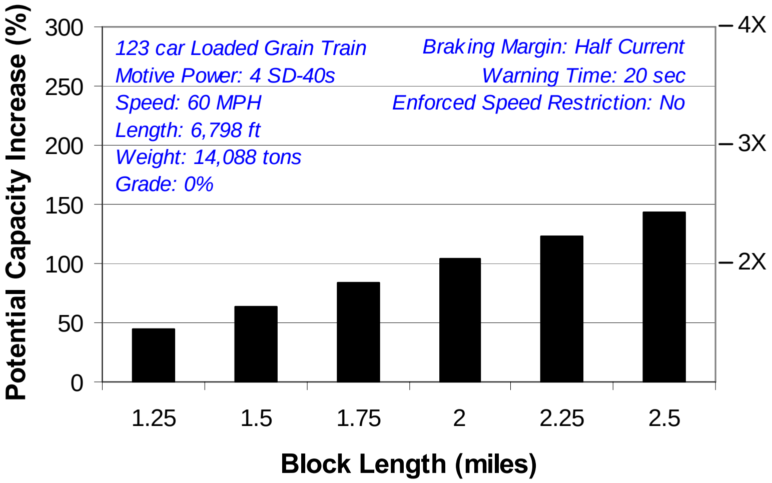
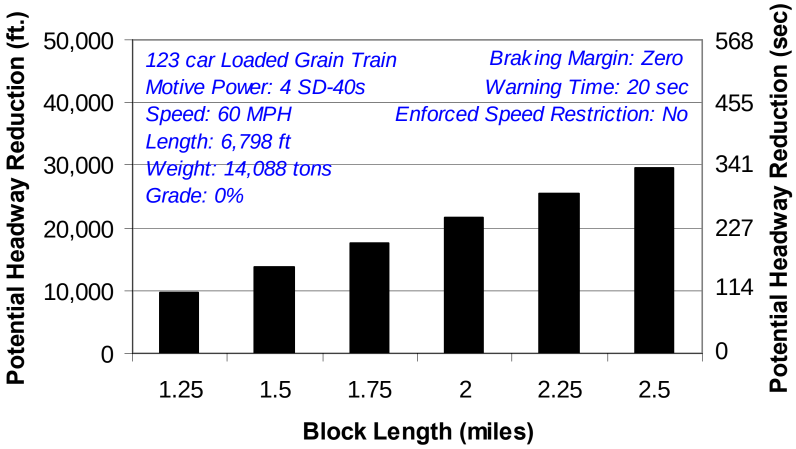


Figure C-7. Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling for a Train Traveling 60 mph on a Level Route, Using a 20-Second Warning, and Half the Current Braking Margin

Zero Braking Margin



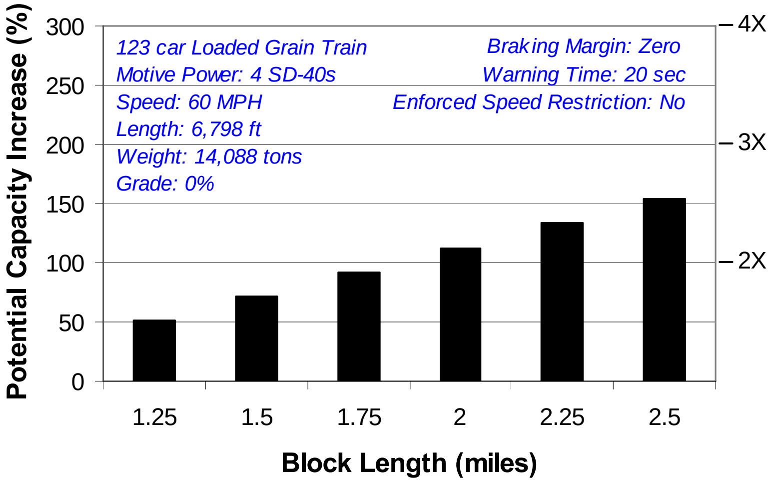
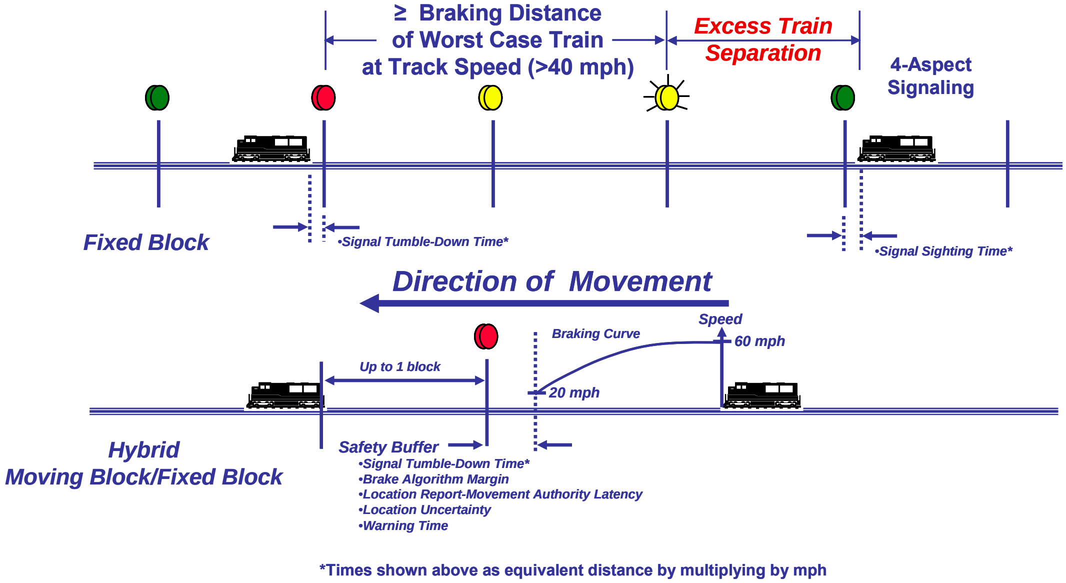


Figure C-8. Potential Headway Reduction and Capacity Increase for Moving Block PTC vs. 4-Aspect Signaling for a Train Traveling 60 mph on a Level Route, Using a 20-Second Warning, and Zero Braking Margin (Ideal Case)

Hybrid Moving Block/Fixed Block—Moving Block with Track Circuits Used for Train Integrity Protection

A hybrid moving block/fixed block vital, positive train control system would use track circuits for train integrity protection. The train integrity loss detection parameter seen in Figure C-1 does not apply, because this approach relies on track circuits and a restricted speed restriction in the block occupied by the leading train for protection against pull-aparts (i.e., no vital EOT is in this configuration to detect a pull-apart within 20 s). This is the mode of operation designed for use in NAJPTC standalone territory. Figure C-9 shows the simulation parameters used for the hybrid moving block/fixed block vital, positive train control system.

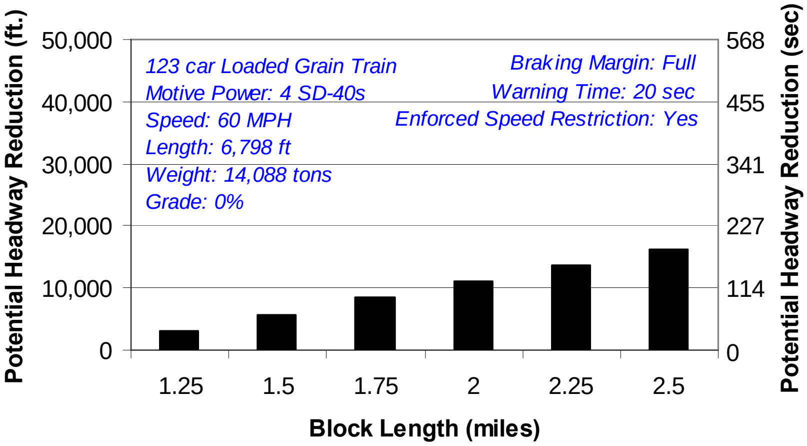


*Times shown above as equivalent distance by multiplying by mph

Figure C-9. Relationship of Moving Block and Conventional Signaling Parameters Used in Analysis of Potential Headway Reduction and Capacity Increase for a Hybrid Moving Block/Fixed Block PTC System Using Track Circuits for Train Integrity Protection

The simulations for this scenario (results shown in Figure C-10) assume that the enforced speed restriction through the occupied block ahead is equal to 20 mph, the upper limit of a restricted speed restriction. Increasing the enforced speed restriction to 30 or 40 mph would bring system performance closer to that of true, moving block, but risk analysis would be needed to justify raising the restricted speed from 20 mph. The NAJPTC system included a railroad configurable parameter for this speed restriction to allow the 20-mph hybrid mode described above, pure moving block, or variations in between.

Train Speed = 60 mph, with Enforced Speed Restriction of 20 mph



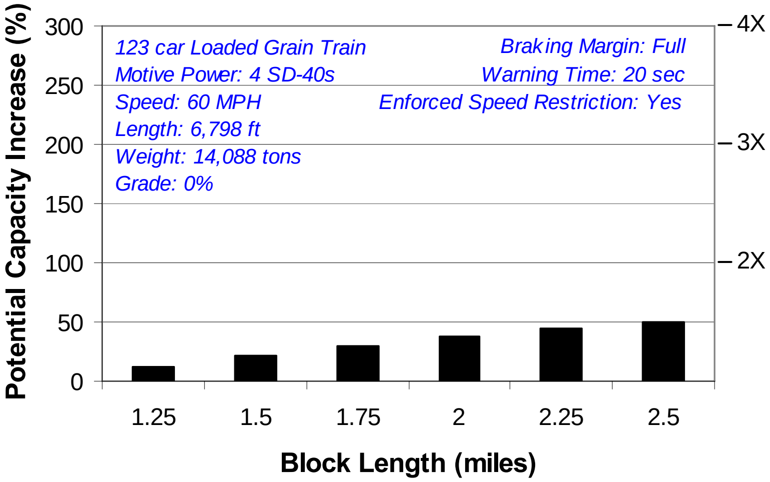


Figure C-10. Potential Headway Reduction and Capacity Increase for Hybrid Moving Block/Fixed Block PTC vs. 4-Aspect Signaling for a Train Traveling 60 mph on a Level Route, Using a 20-Second Warning, and an Enforced Speed Restriction of 20 mph in the Occupied Block Ahead

It should be noted that while moving block (“standalone”) PTC has the potential to increase railway capacity and reduce headways, the Integrated mode (or an overlay PTC system) cannot increase capacity—it can only degrade capacity and headway (due to braking algorithm margin and system delays), because it imposes additional constraints beyond those imposed by the conventional signaling system.

Appendix D.

Deliverables

The NAJPTC project produced the following deliverables.

Software and Document Deliverables

		Current Release
System Specification		Revision (Rev.) 3.3
Concept of Operations		Initial Release for Build 2
Administrative Contract Data Requirement Lists (CDRL)		
A001	Project Management Plan	Rev. A
A002	Project Schedule	Initial Release
B001	Configuration Management Plan	Rev. A
C002	Software Development Plan	Rev. A
C003	Hardware Development and Integration Plan	Rev. A
Software Requirements and Interface Requirements Specification/Interface Design Document (IRS/IDD) CDRLs		
C006/C011	IRS/IDD	Rev. E, CHG 3
C007-A	Software Requirements Specification (SRS)-POS	Rev. E
C007-B	SRS-PTC Office Remote Terminal Server (PORTS)	Rev. B
C007-C	SRS-PTC Office Common Object Library (POCOL)	Rev. E
C007-D	SRS-OBC	Rev. D, CHG 6
C007-E	SRS-LDS	Rev. D
C007-F	SRS-OBD	Rev. E
C007-G	SRS-Work Vehicle	Rev. C
C007-H	SRS-Field Segment (WIU)	Rev. F
Hardware Requirement Specification (HRS) CDRLs		
C008-A	HRS-Office Segment	Rev. B
C008-B	HRS-Locomotive Segment	Rev. E
C008-C	HRS-LDS	Rev. A
C008-D	HRS-Work Vehicle	Initial Release
C008-E	HRS-Field Segment	Rev. D, CHG 1
Software Design Document (SWDD) CDRLs		
C012-A	SWDD-POS	Rev. B
C012-B	SWDD-PORTS	Rev. B
C012-C	SWDD-POCOL	Rev. E
C012-D	SWDD-OBC	Rev. G
C012-E	SWDD-LDS	Rev. E
C012-F	SWDD-OBD	Rev. D

C012-G	SWDD-Work Vehicle	Rev. A
C012-H	SWDD-Field Segment (WIU)	Rev. D
Hardware Design Document (HDD) CDRLs		
C013-A	HDD-Office Segment	Rev. B
C013-B	HDD-Locomotive Segment	Rev. E
C013-C	HDD-LDS	Rev. D
C013-E	HDD-Field Segment	Rev. D
Product Safety Plan CDRLs		
F002	Product Safety Plan	Rev. D
Testing CDRLs		
D001	Contractor Master Test Plan	Rev. C
D002-A/D003-A	Developmental Test Phase Test Plan/Procedures	Rev. H
D002-B/D003-B	Operational Test Phase Test Plan/Procedures	Rev. H
D004-A	Developmental Test Phase Build 1 FAT Test Report	Rev. B
D004-B	Operational Test Phase Build 1 Field/Compliance Test Report—Part 1	Initial Release
D004-C	Operational Test Phase Build 1 Field/Compliance Test Report—Part 2	Rev. A
Training CDRLs		
F003	Training Plan	Rev. A
Other CDRLs		
C001-A	ATCS Communications Trade Study	Rev. A
C009	Requirements Verification Traceability Matrix	Rev. G
C010	System/Segment Design Document	Rev. B
C014	Version Description Document	Initial Release
E001	Site Survey Instrument (Locomotives)	Initial Release
F001	Maintenance Plan Update	Rev. B
F007	Reliability Analysis Update	Rev. B
F009	Availability Analysis Update	Rev. B
F011	Revenue Service Support Plan	Initial Release

Hardware Deliverables

Description	Qty	Unit
Office Segment	1	Lot
Locomotive Segment		
Modification kits for UP locomotives SD-40	6	Each
Modification kits for Amtrak locomotives (P42 type)	16*	Each
Locomotive Segment Spares	1	Lot
Field Segment		
Modification kits for control	22	Each
Modification kits for intermediates	33	Each
Modification kits for electric locked switches	15	Each
Modification kits for hand operator switches	2	Each
Modification kits for grade crossings	74	Each
Modification kits for defect detectors	8	Each
Field Segment Spares	1	Lot
Locomotive Segment		
Conversion of kits for up locomotives SD40 to GP60 type	3	Each

Acronyms

AAR	Association of American Railroads
AEI	Automatic Equipment Identification
ATC	Automatic Train Control
ATCS	Advanced Train Control System
CAD	computer-aided dispatch
CBTC	communication-based train control
CDRL	contract data requirements list
COTS	commercial off-the-shelf
CSMA	carrier sense multiple access
CTC	centralized traffic control
DGPS	Differential Global Positioning System
DP	distributed power
EIC	employee in charge
EOT	end of train
FRA	Federal Railroad Administration
GPS	Global Positioning System
GCOR	General Code of Operating Rules
IDOT	Illinois Department of Transportation
NAJPTC	North American Joint Positive Train Control
INS	inertial navigation system
LAP	link access protocol
LDS	location determination system
MIS	management information system
OBC	onboard computer

OBD	onboard display
POCOL	PTC Office Common Object Library
POD	Point Of Discrimination
PORTS	PTC Office Remote Terminal Server
POS	PTC Office Server
PSP	product safety plan
PTC	positive train control
RRF	Railroad Research Foundation
RVCCM	requirements verification conditions and criteria matrix
SWDD	software design document
TDMA	time division multiple access
TPM	technical performance measure
TTCI	Transportation Technology Center, Inc.
UP	Union Pacific
WIU	wayside interface unit