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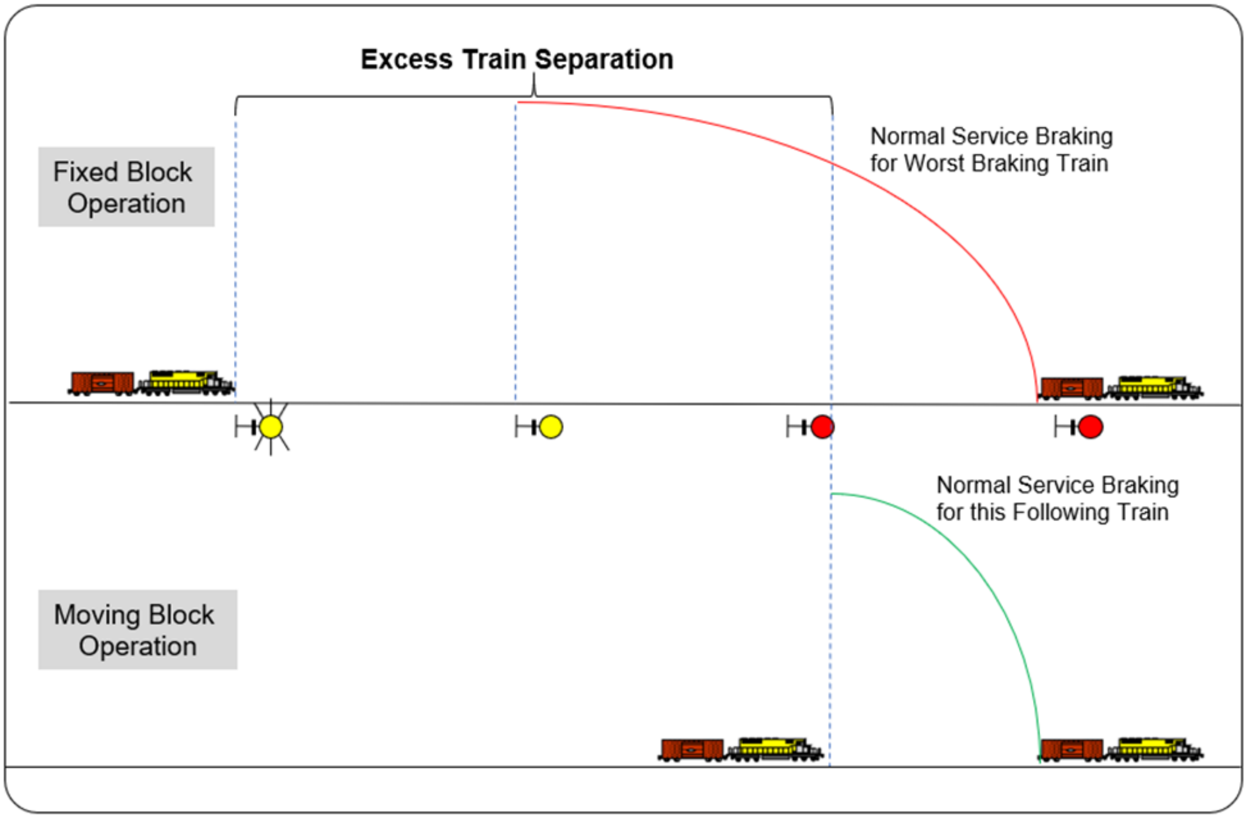
of Transportation

**Federal Railroad
Administration**

**Office of Research,
Development and Technology
Washington, DC 20590**

Higher Reliability and Capacity Train Control



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14. ABSTRACT

Researchers developed new concepts of train control systems that could potentially offset the negative impacts to train operations introduced by the current implementation of PTC (Overlay PTC). They investigated the effects on railroad network operation caused by the operation of PTC, such as the conservatism of train braking enforcement algorithms, impacts on train operation due to failure of PTC components and human operation errors, as well as the improvements provided by the proposed new train control methods.

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1 yard (yd) = 0.9 meter (m)	1 meter (m) = 3.3 feet (ft)
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	= 1.1 short tons
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1 quart (qt) = 0.96 liter (l)	
1 gallon (gal) = 3.8 liters (l)	
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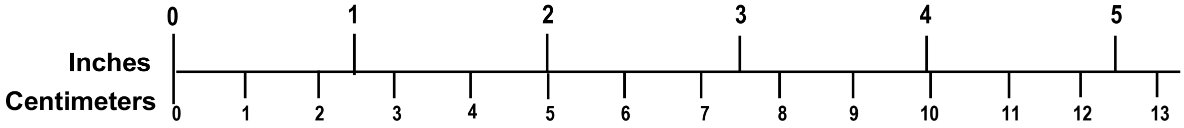

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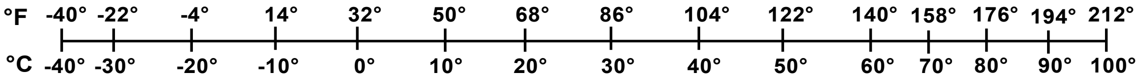

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Executive Summary

Transportation Technology Center, Inc., (TTCI) developed and analyzed new train control systems concepts that could potentially offset the negative impacts to train operations introduced by the current implementation of Positive Train Control (PTC – referred to throughout this report as Overlay PTC). The results indicate that the proposed train control methods may have the ability to mitigate the negative impacts caused by Overlay PTC as well as increase overall efficiency beyond what can be achieved without PTC.

Researchers analyzed the performance of three proposed new train control methods – Enhanced Overlay PTC (EO-PTC), Quasi-moving Block (QMB), and Full-moving Block (FMB) – built upon the current Overlay PTC design. EO-PTC, if implemented on all PTC-controlled tracks, was estimated to provide a slight reduction in total travel time, while QMB and FMB could provide further reduction, which could be used to increase overall network capacity.

The proposed train control methods can also provide additional capacity gains as trains will be able to operate with shorter headways. For the specific operational scenarios and implementations modeled, EO-PTC, if implemented in all signaled territories, could provide a capacity increase of approximately 4.2 percent when compared to railroad performance before implementation of PTC, while FMB could provide approximately 10.4 percent.

The results indicate that all of the proposed train control methods had the potential to not only offset the impact caused by Overlay PTC but could also provide capacity gains.

The analysis investigated the effects on railroad network operation caused by the operation of PTC, such as the conservatism of train braking enforcement algorithms, impacts on train operation due to failure of PTC components and human operation errors, as well as the improvements provided by the proposed new train control methods. The research team modified the railroad network simulation tool used in the project to incorporate PTC features and calculate total train travel times for multiple operational scenarios (e.g., signaled single-, double- and triple-track territories; non-signaled territories), configured with typical railroad operational characteristics at multiple train density levels. The frequency and duration of events that affect train operation due to Overlay PTC operation were based on actual field data collected by participant railroads associated with their PTC operation at the time the data was collected, and extrapolated to project the frequency and duration of events at the time when PTC was fully deployed on all required lines.

The proposed train control methods are at different levels of readiness for deployment. EO-PTC can be implemented without software or hardware changes, requiring only changes to the configuration of the track database, modification of rules, and training. QMB, when configured to utilize technology such as Positive Train Location at the End-of-Train (PTL-EOT) and centralized interlocking, requires development of new, or modification to existing, train control components (hardware and software) as well as the development of these new technologies. These technologies are not fully ready for PTC yet and require the completion of current developments. FMB will substantially leverage off of QMB and will require the use of an alternate broken rail and rollout detection system. This report provides a practical roadmap for quickly migrating to FMB, with each step heavily leveraging off of the prior train control method.

Based on the concepts defined during the development of this project, multiple spin-off projects were initiated for EO-PTC, QMB, FMB and associated technologies. As of late 2019, the Federal Railroad Administration had awarded multiple spin-off projects from the Higher Reliability and Capacity Train Control (HRCTC) program, and other projects had been selected by railroad committees had selected other high-priority projects for development.

1. Introduction

1.1 Background

Signaling and train control systems support safe and efficient railroad operations. Concepts for new train control methods and technologies have the potential to improve safety, capacity, and average velocity as well as to reduce life cycle costs. Current Positive Train Control (PTC – referred to throughout this report as Overlay PTC) systems provide safety enhancements but also increase lifecycle costs due to the addition of equipment on locomotives, along the wayside, and in the back office. Overlay PTC systems hinder railroad operations because they maintain all the constraints of the underlying conventional signaling system with added conservatism to account for imperfect input information and the additional failure modes they introduce. These impacts manifest themselves as the stopping or slowing of trains prematurely or unnecessarily due to:

- Equipment/system failures – e.g., hardware failures, design errors in hardware or software
- Message communication failures – Due to loss of over-the-air or backbone messages; excessive communications latency or insufficient throughput can also be detrimental to train operations.
- Global Positioning System (GPS) issues – Due to loss of signal or errors that could result from multi-path, diminished satellite geometric dilution of precision (GDOP), or satellite outage.
- Premature warning or enforcement braking – Due to conservatism in the braking prediction algorithm
- Incorrect data – For example, track data, consist characteristics, or configuration parameters
- Operator error – Occurring during initialization or operation

These events delay trains and reduce railroad capacity at a time when railroads are approaching capacity limits in many areas. The degradations are greatest in high-traffic-density areas, where improvements (not degradations) are needed the most. Further, these locations are where delays in one train are most likely to cause delays in other (e.g., following) trains. Furthermore, system reliability issues can also impact safety because when PTC equipment fails, it can no longer provide its intended safety functionality.

It is critical to the nation's economy, businesses, as well as citizen safety and well-being to keep freight, passenger and commuter traffic flowing efficiently, smoothly and safely. Consequently, there is a need to improve the reliability and capacity of today's train control systems, especially in areas of high traffic density.

Because of these issues, the Federal Railroad Administration (FRA) tasked Transportation Technology Center, Inc., (TTCI) to undertake a comprehensive study of methods and technologies to improve train control effectiveness and efficiency and to mitigate or compensate for these impacts. TTCI investigated a spectrum of Higher Reliability and Capacity Train Control (HRCTC) concepts, ranging from improving conventional train control systems to integration of new technologies/concepts and improvements in reliability and maintenance that would mitigate or offset these impacts.

The HRCTC concepts are built upon existing Overlay PTC implementation to allow for staged migration to the target state with incremental return on investment (ROI); i.e., individual modes and supporting subsystems of HRCTC can be fielded at different times in different PTC-controlled territories and each stage is capable of providing benefits on its own. Trains will be able to seamlessly transition between areas with and without the proposed new methods and technologies, just like trains transition today among train control territories, such as Centralized Traffic Control (CTC), current of traffic, and track warrant control (TWC). Many tradeoffs must be performed to achieve industry standards that meet the needs of the various affected railroads and that allow maximal flexibility for variants in implementation and sourcing.

1.2 Objectives

The objectives of this project were to:

- Understand the observed and potential operational and safety impacts of Overlay PTC, particularly as related to effects on railroad capacity and system availability.
- Develop methods to increase railroad capacity and improve PTC system availability through a multi-faceted study that considers various operations-related elements (not only PTC). This includes elements that are on board trains, at the wayside, and in the back office, as well as the communications network that interconnects them.
- Develop the HRCTC concepts and high-level migration roadmap for the deployment of those concepts.
- Develop a high-level approach that will allow for staged implementation of identified train control methods and, where appropriate, migration to these methods with incremental ROI (i.e., individual subsystems will be fielded at different times in different areas and they must each be capable of providing benefits on their own).
- Develop an approach that will provide trains with the ability to seamlessly transition between areas with and without these technologies, just like trains transition today among train control territories such as CTC, current of traffic, track warrant control (TWC).
- Develop an approach that will meet the needs of the various affected railroads and allow for maximal flexibility for variants in implementation and sourcing.

1.3 Overall Approach

The development of the project included regular meetings with the project's Advisory Group (AG) to present the progress of the project, discuss and make decisions about project-related issues, discuss the concepts of the proposed train control methods, as well as present and review results of technical analyses. The concepts for the proposed train control methods were based on the results of multiple analyses and were continuously improved during discussions with the AG. The work was conducted with a combination of tasks:

1. Researchers developed a high-level conceptual analysis of candidate methods that could help mitigate the negative impacts of Overlay PTC. The concepts were initially prepared by a team composed of railroad experts specialized in train control methods and revised with the project's AG in several meetings.

2. As required during the development of the train control concepts, researchers developed technical analyses with both analytical and simulation tools to assess their feasibility. The results of those analyses were shared with the AG to support project decisions.
3. Researchers prepared a white paper report with the results obtained and submitted to the AG.
4. They prepared the requirements for PTC simulation that included the description of system behavior in case of occurrence of exceptional events related to PTC operation (i.e., failure of PTC components or human error when operating PTC). The requirements were distributed to the software development providers that implement railroad network simulation software. TTCI followed-up on the development of the PTC features implemented to satisfy the requirements.
5. Researchers analyzed Overlay PTC operation field data collected by railroads containing information about the occurrence of exceptional events during Overlay PTC operation, used to calculate the average frequency of those events and time to restore normal operation.
6. The research team, with direction and input from the AG, selected the operational scenarios required to evaluate the impact of Overlay PTC operation and the performance of the various train control methods.
7. The team developed models in the railroad network simulation tool for the selected operational scenarios.
8. They ran network simulations of multiple cases using the PTC features and feeding the model with the results of the analysis of the Overlay PTC operation field data.
9. They developed tools to compile the results of the simulations and generate comparative performance analysis. The results of the performance analysis were presented to the AG.
10. In parallel with the development of the simulation and analysis tasks, the concepts for the new train control methods were being continuously improved. New technologies and modifications to process were incorporated into the proposed train control methods as required. Spin-off projects were proposed, reviewed, and approved by the AG.
11. Based on the concepts of the proposed train control methods and the current stage of development of technologies, the research team developed a high-level migration plan and feasibility analysis.

1.4 Scope

The project included the analysis of Interoperable Train Control (ITC)-compliant systems only. TTCI assumed that the core architecture of the Overlay PTC system will be retained; i.e., alternative architectures that could replace the entire system or core system designs were not considered. The train control methods proposed as the evolution of the Overlay PTC system considered the use of new technologies that are either already being developed or in advanced conceptual stages and could potentially be fully implemented within the lifetime of PTC.

The analysis of the performance of the train control methods and impacts on operations resulting from those methods was developed for selected operational scenarios considered to be representative of the majority of U.S. railroad operations. researchers developed the analysis using both analytical methods and simulation. The simulations of the operational scenarios included multiple train density level runs, except for the dense urban area (DUA) scenario, for which the train density was based on 2020 train traffic levels. The analysis included assessment of the capacity of the train control methods to recover from typical operational disruption scenarios that can occur in daily operations; i.e., exceptional scenarios such as long duration operational disruptions were not analyzed. The simulation of the proposed train control methods were limited to restrictions of the tool used in the analysis; for example, moving block operation was emulated using fixed blocks configured with 0.1-mile lengths.

Researchers developed a limited analysis of the PTC system availability, restricted to the identification of the main contributors to impacts in railroad operation. The analysis was based on PTC operation field data collected by some of the participant railroads containing information about the occurrence of exceptional events during Overlay PTC operation. The impact on operations caused by underlying systems (such as the signaling system) was not included in the analysis.

This work does not include analysis of costs to implement the proposed train control methods. The high-level migration plan describes the sequence of generic steps to implement the proposed train control methods and key aspects that need to be considered during the ROI analysis for a particular territory.

1.5 Organization of the Report

The report is divided in the following sections:

- Section 2 describes the concepts of the proposed train control methods, the technologies involved and suggested steps for evolution. Sub-sections describe core principles of each of the proposed train control methods and related spin-off projects
- Section 3 describes the methodologies and tools used to assess the impacts of the introduction of Overlay PTC and the performance of the proposed train control methods. It also contains results obtained through applying the methodologies and tools to evaluate the performance of the proposed train control methods.
- Section 4 describes the migration strategies for the proposed train control methods. It includes a section with a generic plan that provides the framework and roadmap for the migration to any train control method and separate sections with specifics for each of the train control methods.
- Section 5 describes the assessment of the feasibility of the technologies necessary for the implementation of the proposed train control methods, describing current stages of development, challenges for development and current initiatives for implementation.
- Section 6 contains the conclusions of the project.
- Appendices A–G contain several sections with detailed data and/or descriptions of methods used in the analysis. They also contain the Requirements for Implementation of PTC Features for Railroad Network Simulation.

2. HRCTC Concepts and PTC Evolution

2.1 Current System: Overlay PTC

Overlay PTC is a safety overlay system, meaning it enforces rules of the train control method on which it is overlaid and does not replace the pre-existing conventional train control system. In signaled territory, Overlay PTC enforces compliance with the fixed block signaling system as explained below.

2.1.1 Conventional Fixed-Block Signaling

Track circuits are one of the basic components of conventional fixed block railroad signaling systems. Conventional signal systems typically use track circuits to perform three functions:

1. Detect occupancy in each block.
2. Detect broken rail in each block.
3. Communicate the operational status of each block to adjacent blocks.

The track is separated into electrically isolated sections (blocks) to create track circuits. Typically, insulated joints in the rails are used to isolate each block. A voltage is placed across the rails at one end of the block, and the presence or absence of electrical current is detected at the opposite end of the block. If sufficient current is detected, the block is considered clear of shunting vehicles or broken rails; if sufficient current is not detected, the block is considered not clear as there may be a vehicle present, a broken rail, or a failed track circuit component.

In conventional signaling systems, signal aspects are determined by the status of the block over which the signal governs movement, as indicated by the track circuit in that block, as well as the status of adjacent blocks. Information about the status of each block is typically transmitted to adjacent blocks using coded track circuits, although other methods are used in certain cases.

The minimum required length of the track circuit is based on worst-case braking distances at track speed and the number of signal aspects that can be displayed at that location. For example, with four-aspect signaling, the blocks are spaced such that two blocks represent no less than the distance of normal service braking for the worst-case braking train traveling at Maximum Authorized Speed (MAS). This supports safe separation between trains, as seen in Figure 1. If a train is detected on a given block, the signals for the preceding blocks will be ordered by restrictiveness: red (Stop, Stop-and-Proceed, or Restricting), yellow (Approach), flashing yellow (Advance Approach), and Green (Proceed). Flashing yellow can be used to indicate proceed and prepare to stop at second signal or proceed and reduce speed before passing next signal.

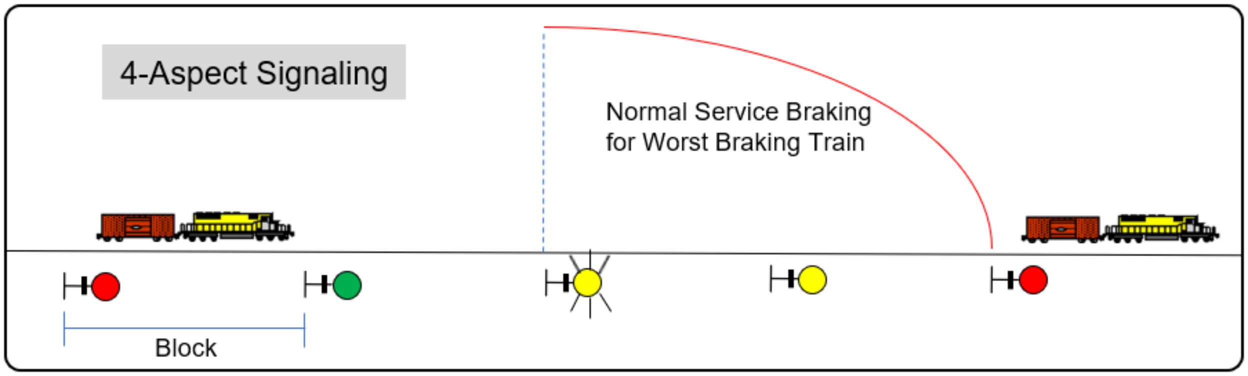

Figure 1. Schematic of Four-Aspect Signaled Route Configuration

2.1.2 Positive Train Control

The Rail Safety Improvement Act of 2008 (RSIA'08) mandates implementation of interoperable PTC on a significant portion of U.S. rail lines. PTC, as defined in RSIA'08, is a system designed to prevent train-to-train collisions, overspeed derailments, unauthorized incursions into established roadway work zones, and movement of a train through a mainline switch in the wrong position. There are a few different systems currently being implemented to satisfy the PTC requirements. The most predominant of these systems is defined by the ITC standards.

Figure 2 illustrates the high-level architecture of an ITC-compliant system. The locomotive onboard segment in this example determines the location of the train relative to the track and critical assets along the track using GPS, tachometer, switch position information, and an onboard track database. Consist and route information, among other things, are provided to the locomotive onboard system from the PTC back office during initialization. Wayside Interface Units (WIUs) installed at switch and signal locations along the track periodically broadcast the status of the switches and/or signals they are monitoring over the communications network. As the train approaches these locations, the status messages are received by the locomotive onboard system. Work zones, temporary speed restrictions, and other bulletin data are provided to the locomotive onboard system by the PTC back office over the communications network.

All the operational data provided to the locomotive onboard system is processed to determine the operational limits (authority and speed restrictions) for that train. The locomotive onboard system regularly updates the predicted braking distance of the train and warns the train crew when the system is within a specified time of applying a penalty brake enforcement being applied to avoid violating an authority or speed limit. Additionally, should the locomotive crew fail to take appropriate action to prevent the violation, the onboard segment will enforce with a penalty brake application to stop the train to avoid the violation.

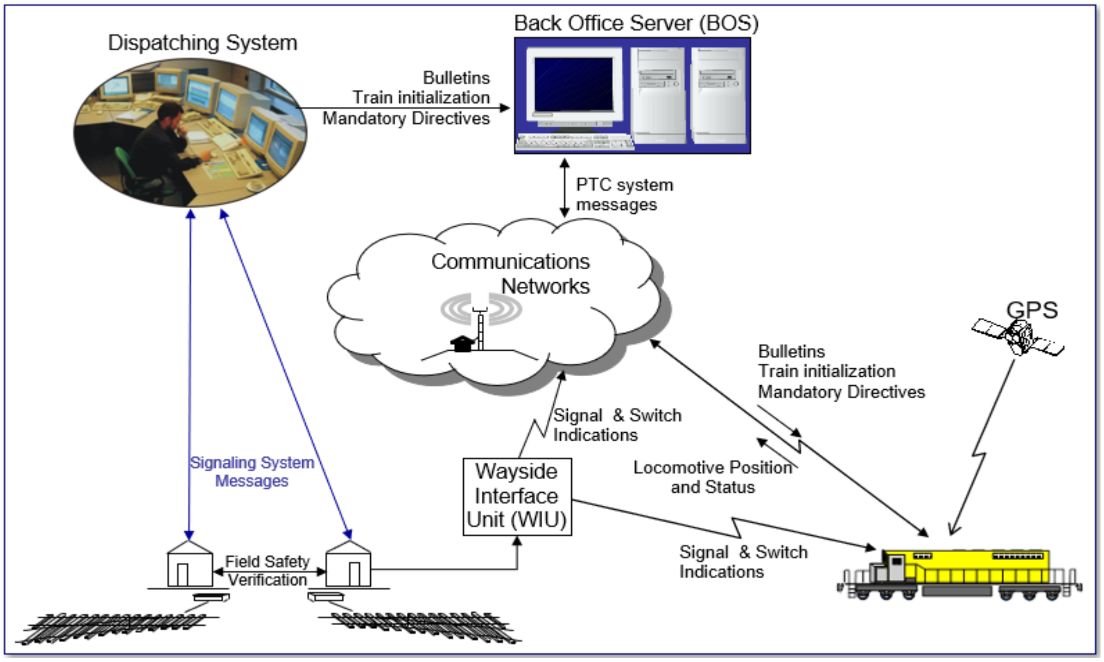

Figure 2. High-Level Architecture of ITC System

2.2 PTC Reliability and Capacity Improvement Overview

The evolutionary path of PTC to achieve higher reliability and capacity gains can come from three groups of improvements:

1. New methods of train control: Adoption of new concepts for train control by exploring the capabilities made available with the introduction of Overlay PTC implementation.
2. New technologies: Integration of new technologies that become either feasible or capable of achieving their full capacity with the introduction of Overlay PTC.
3. Reliability, Availability, and Maintainability (RAM) improvements: Implementation of improvements in the reliability and maintainability of components and/or systems that impact railroad efficiency or increase exposure to hazard under PTC operations.

Three new train control methods have been identified as the potential evolutionary stages from Overlay PTC:

1. **Enhanced Overlay PTC (EO-PTC):** This consists of the realization of operational efficiency by not enforcing speed restrictions at Approach and Advance Approach indications when the PTC onboard is in the "active" state. This is a straightforward implementation that only requires reconfiguration of input tables of the Overlay PTC onboard system and changes to railroad operational rules.
2. **Quasi-Moving Block (QMB):** This consists of governing any train operation in PTC territory by the issuance of non-overlapping movement authorities, known as PTC Enforceable Authority (PTCEA). This offers more consistency in train control as well as safety improvements over current Overlay PTC, including the ability to provide rear-end collision protection and collision protection within a joint authority. Additionally, QMB

offers improved capacity (if certain optional technologies are integrated) and reliability and is a logical step in the migration to a full-moving block train control method.

3. **Full-Moving Block (FMB):** This a concept where the track occupancy is determined by a train's footprint (from front- to rear-end) instead of fixed blocks (such as track circuits). In FMB, the system nearly continuously updates PTCEAs based on each train's footprint.

Sections 2.2, 2.3, and 2.4 describe the core concepts of these train control methods in further detail. Figure 3 illustrates the typical evolution path of those PTC train control methods. It is possible, however, to skip one or more stages, as discussed in more detail in Section 4.

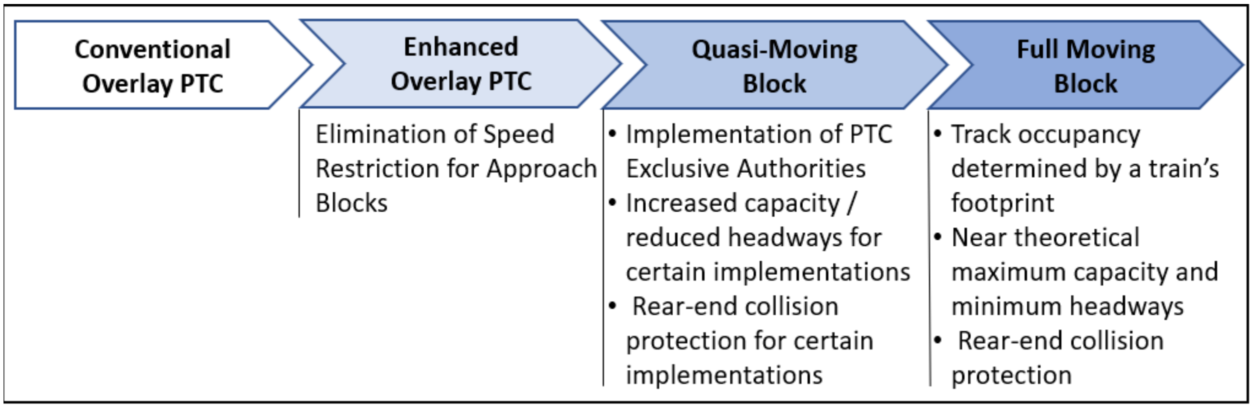

Figure 3. PTC Evolutionary Path Diagram

EO-PTC can provide increased capacity, as trains are allowed to operate at higher speeds when operating in blocks with Approach and Advance Approach indications with EO-PTC, which can result in shorter headways when operating above 30 mph, as illustrated in Figure 4.

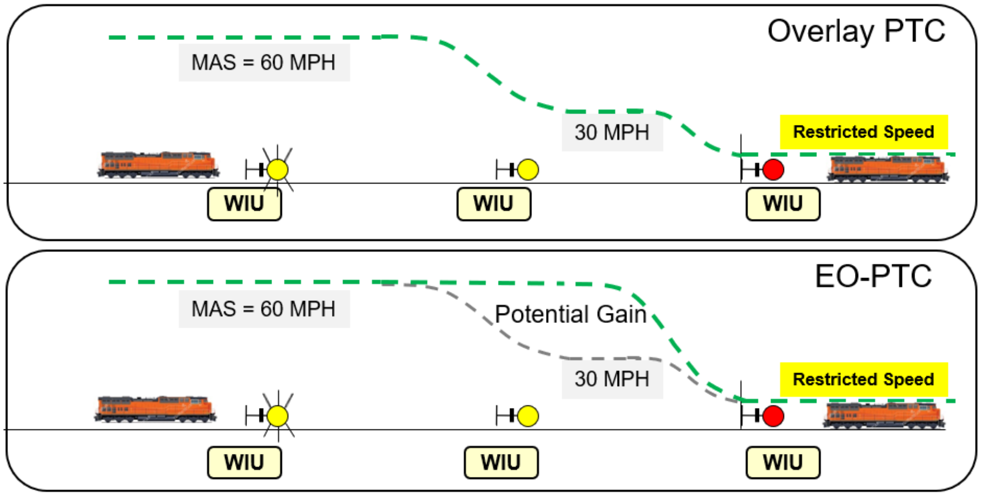

Figure 4. Speed Limits under Overlay PTC and EO-PTC and Potential Capacity Gain

In QMB, train movements are limited by the same physical constraints as Overlay PTC and EO-PTC, i.e., track circuit boundaries. However, there are two ways railroads can expand their capacity with QMB beyond the gains obtained with EO-PTC. The first way is by shortening track circuits, such as by halving track circuit lengths in signaled territories where train traffic volumes are reaching practical capacity. Even though this is theoretically possible with any signaling system, it can be done at lower cost in QMB, as it can be implemented without the need to increase the number of physical signals nor aspects.

The second way QMB can provide capacity gains is when implemented with two other emerging concepts:

- **Next Generation Track Circuits (NGTC):** NGTC is a technology that allows for the determination of the integrity of an occupied track circuit between the boundary of the track circuit up to the occupying train's footprint.
- **Positive Train Location – End-of-Train (PTL-EOT):** PTL-EOT is a technology that allows a train to report its rear-end position in a vital way.

Combining the introduction of PTCEAs in QMB with the ability to detect broken rail behind a train with NGTC and the determination of the rear-end location of a train with PTL-EOT, QMB can also provide capacity gains in following moves. Figure 5 illustrates a following move operation with NGTC and PTL-EOT. When Train 2, which is following Train 1, reaches the boundary between track circuits 1 and 2, it has its PTCEA extended at MAS with a target to stop at the rear-end location of Train 1, which is the last known location of Train 1 when Train 2 reached the boundary. From that point on, the PTCEA for Train 2 will be extended to the rear end of Train 1, but now with a Restricted Speed restriction (RSR), as it is not possible to determine the integrity of the rail until Train 1 completely clears track circuit 2.

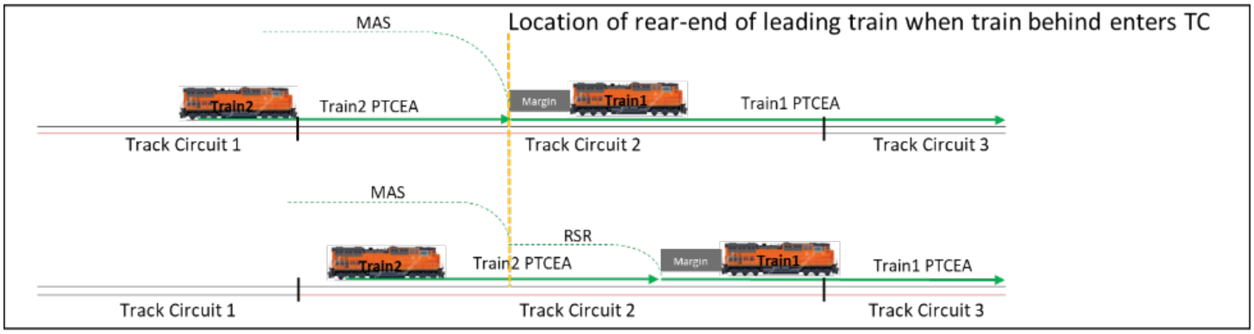

Figure 5. QMB Operation with NGTC and PTL-EOT

The implementation of QMB also facilitates the implementation of a centralized interlocking (CIXL) architecture, particularly because the authorization of train movement is not granted by visual signals, but by PTCEAs, which are already generated in a central component with QMB. Figure 6 illustrates the implementation of CIXL with QMB.

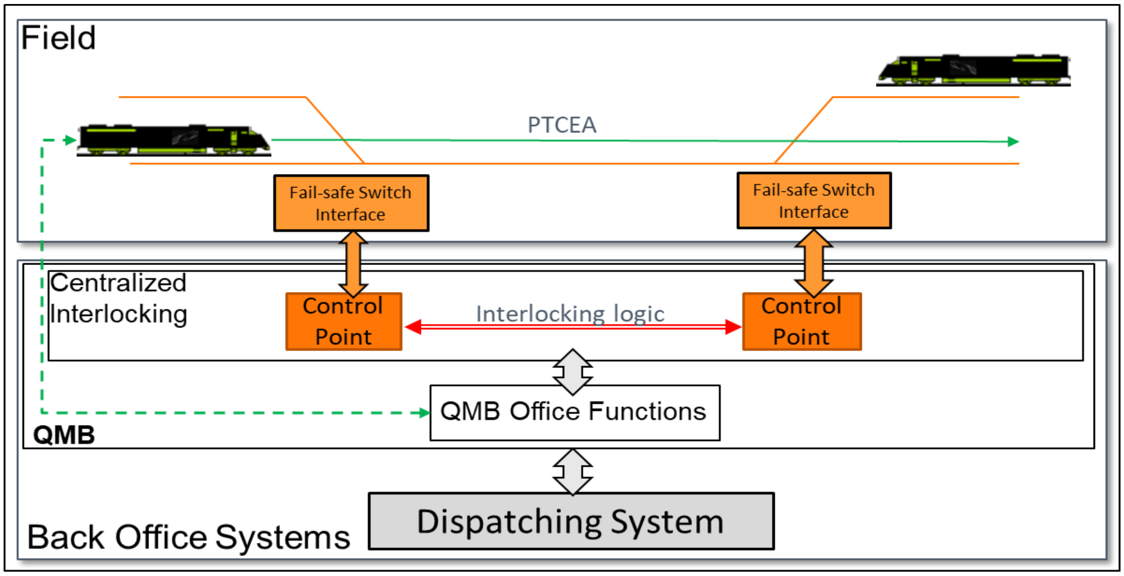

Figure 6. Centralized Interlocking Architecture Diagram

FMB is the final stage of evolution of PTC envisioned in terms of train headway reduction, as a train in a following move can operate continuously based on its braking curve to the rear-end of a leading train (see Figure 7). The excess train spacing when operating at speeds above 30 mph under conventional fixed block train control systems is eliminated. An additional objective of FMB is to replace track circuits with a more cost-effective method of detecting rail breaks and rollouts.

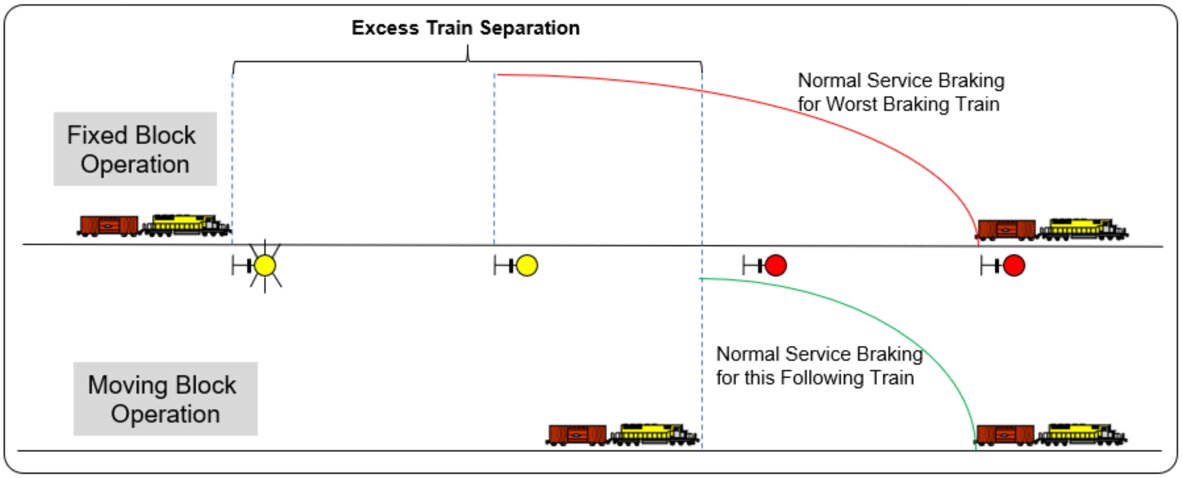

Figure 7. Fixed and Moving Block Operation and Excessive Train Separation

The implementation of FMB, however, requires addressing the following issues:

- Identification of broken rail between the front end of a following train and the rear end of train ahead when the trains are separated by as little as the braking distance of the following train. This requires a broken rail detection system that is not tied to fixed block boundaries. Without track circuits, an alternative method of protection with regard to rollout movements must be provided. In traditional signaling systems (such as

Centralized Traffic Control), these functions are provided solely by conventional track circuits, which does not satisfy the requirement for FMB.

- Continuous vital location of trains (front and rear-end) to safely keep trains separated, e.g., PTL-EOT.

Figure 8 illustrates how new concepts/technologies could be introduced as PTC evolves.

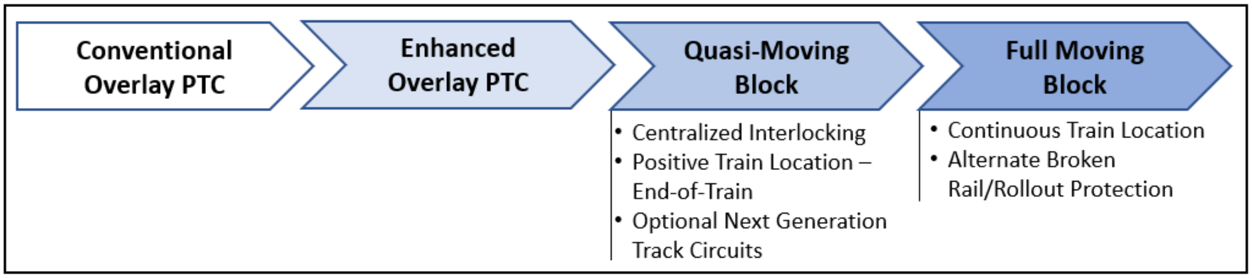

Figure 8. PTC Evolution and Introduction of New Concepts/Technologies

As PTC evolves in different territories, various train control methods and configurations become possible. Depending on the chosen configuration, system components and functions are added, while existing components and functions are changed or eliminated. Table 1 summarizes the main changes in system design when evolving from one train control method and configuration to another.

Table 1. Summary of System Design Changes as Train Control Methods and Configurations Evolve

Type of Territory	From (train control method/configuration)	To (train control method/configuration)	System Design Changes
Signaled	Overlay PTC	EO-PTC	Reconfiguration of signal indication (e.g., via track data modification) to relax Approach and Advance Approach speed restrictions
	EO-PTC	QMB keeping field interlocking and without NGTC and PTL-EOT	System Design Changes from Overlay PTC to EO-PTC, plus: 1) Introduction of exclusive PTC Enforceable Authorities (PTCEA) in all territories, for all types of trains, at all times 2) PTCEAs periodically rolled up with RSR during CFM based on non-vital rear-of-train location determination. 3) Elimination of field signals 4) Track circuits can be shortened at lower cost.

Type of Territory	From (train control method/configuration)	To (train control method/configuration)	System Design Changes
	EO-PTC	QMB keeping field interlocking and with addition of NGTC and PTL-EOT	System Design Changes from EO-PTC to QMB without NGTC and PTL-EOT, plus: 1) Vital rear-of-train location determination with PTL-EOT 2) Improved broken rail detection with NGTC 3) PTL-EOT and NGTC together allow train operation at track speed in portion of an occupied block during close following moves.
	EO-PTC	QMB with the addition of CIXL, NGTC and PTL-EOT	System Design Changes from EO-PTC to QMB with NGTC and PTL-EOT, plus: 1) Migration of interlocking functions to the back office 2) Decommissioning of field interlocking components
	QMB with field interlocking end PTL-EOT (but no NGTC)	FMB with field interlocking	Introduction of alternative broken rail detection that supports track speed anywhere in an occupied block (up to braking distance from the train ahead).
	QMB with field interlocking, NGTC and PTL-EOT	FMB with field interlocking	Introduction of alternative broken rail detection (alternative to NGTC) that supports track speed anywhere in an occupied block (up to braking distance from the train ahead).
	QMB with CIXL and EOT-PTL (but no NGTC)	FMB with CIXL	Introduction of alternative broken rail detection that supports track speed anywhere in an occupied block (up to braking distance from the train ahead).
	QMB with CIXL, NGTC and PTL-EOT	FMB with CIXL	Introduction of alternative broken rail detection (alternative to NGTC) that supports track speed anywhere in an occupied block (up to braking distance from the train ahead).
Non-signaled	Overlay PTC	FMB with optional CIXL and alternative broken rail detection	1) Introduction of exclusive Enforceable Authorities (PTCEA) in all territories, for all types of trains, at all times 2) Vital rear-of-train location determination with PTL-EOT 3) Optional introduction of alternative broken rail detection 4) Optional introduction of interlocking functions in the back office

Note that not necessarily all railroad territories will have to evolve to more advanced train control methods and configurations nor integrate/deploy all new technologies/concepts. As new train control methods and configurations are added (e.g., EO-PTC, QMB), it is not necessary to eliminate the old methods and configurations (e.g., Overlay PTC) from the system design. A railroad's decision on which train control method and configuration to apply to each territory can be made on a case-by-case basis, depending on ROI analysis that a railroad may develop. It is possible that a railroad will operate with one train control method and use supporting technologies in some territories and a different method in other territories. This is analogous to a particular railroad having some of its track operating under CTC, other track under ABS-TWC, and yet other territory under TWC. Section 3 contains the results of analysis of expected benefits of the HRCTC concepts under various operational scenarios and Section 4 elaborates further on PTC migration roadmap. Railroads can use those as reference to plan their own evolution of PTC.

Improvements in the RAM of PTC components and subsystems can help offset the impacts caused by their failure or insufficient performance. Increasing the mean time between downing events (MTBDE) and/or reducing the mean time to repair (MTTR) of PTC components are always key objectives in a RAM growth plan; therefore, it is important to determine the impact caused by failures of PTC components or incorrect use of the system, to determine which ones to prioritize during RAM analysis. Section 3.1.5 describes the types of PTC Impact Events (PTCIEs) that were included in the analysis, while Section 3.2 includes results showing the contribution of PTCIEs to the performance of train control methods.

The realization of the benefits expected from the proposed HRCTC concepts depends in many cases on the availability of new technologies, not just as concepts or experiments, but as systems that are feasible to be deployed, dependable, and capable of integrating with other systems. Section 5 contains a high-level feasibility analysis of those technologies, including the description of their current stage of development and gaps to achieve a feasible and deployable product.

Note that FRA has funded a number of additional projects to advance the HRCTC concepts herein described:

- EO-PTC concept of operation (ConOps), safety analysis and implementation plan (completed in July 2019)
- QMB ConOps, safety analysis, feasibility analysis and implementation plan
- QMB system requirement specification (SysRS)
- Centralized Interlocking research
- PTC Reliability, Availability and Maintainability analysis and growth plan
- PTL-EOT requirements specification
- Next generation track circuit ConOps
- Alternative broken rail detection research

2.3 Enhanced-Overlay PTC (EO-PTC)

The fundamental concept of EO-PTC is that wayside signals no longer convey the authorized speed within a block governed by Approach or Advance Approach signal indications. Instead, the braking algorithm calculated by the onboard segment[1] determines the train's safe operating speed within these blocks. Increased speed within Approach and Advance Approach blocks allows closer following distances for PTC-equipped trains, resulting in efficiency gains without compromising safety.

The core of the proposed EO-PTC implementation is a modification of the track database signal mapping in such a way that WIU device status codes for the Approach and Advance Approach status updates are mapped to a signal code indicating "Clear." No modification of the onboard software is planned, as the new mapping is automatically applied when the updated track database is received by the onboard segment. PTC-equipped trains and their crews see a Clear indication on the onboard display when approaching signals with Approach and Advance Approach aspects. Non-communicating trains follow the existing (more restrictive) wayside aspect.

Figure 9 illustrates the signal indications for Approach and Advance Approach blocks, respectively, for Overlay PTC and EO-PTC territories. In EO-PTC territories, the onboard track database maps the Wayside Status Messages (WSM) related to the Approach signals to a Clear code signal and display a green track line (as opposed to a yellow track line), as seen in Figure 10. This method allows all PTC trains to travel at MAS in these blocks if the calculated braking distance is not beyond the stop target. MAS is the highest speed permitted for the movement of trains permanently established by timetable/special instructions, general order, or track bulletin, as defined in 49 CFR 214.7.

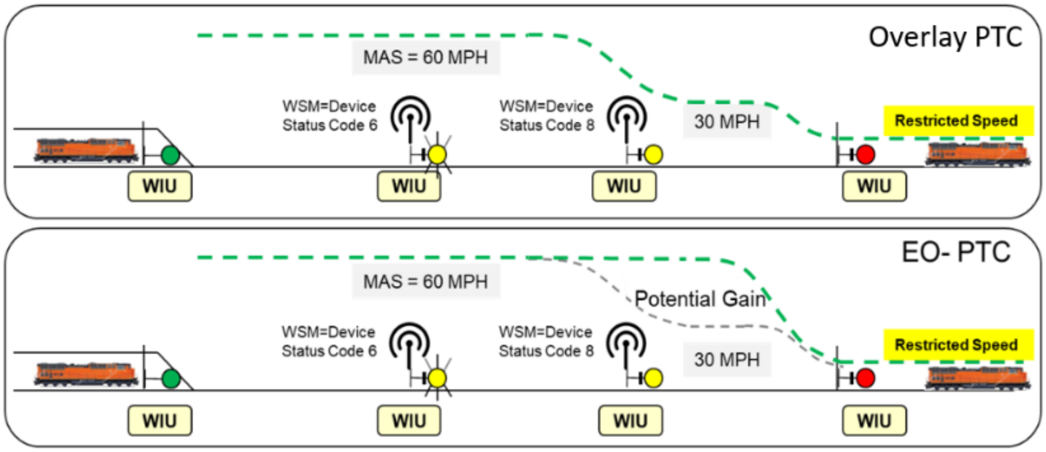

Figure 9. Wayside Signal Aspects and WSMs in Overlay PTC and EO-PTC

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[1] The onboard segment considers track speed restrictions due to curvature, grade, and condition of the track, as well as speed restrictions imposed by the timetable or other instructions.

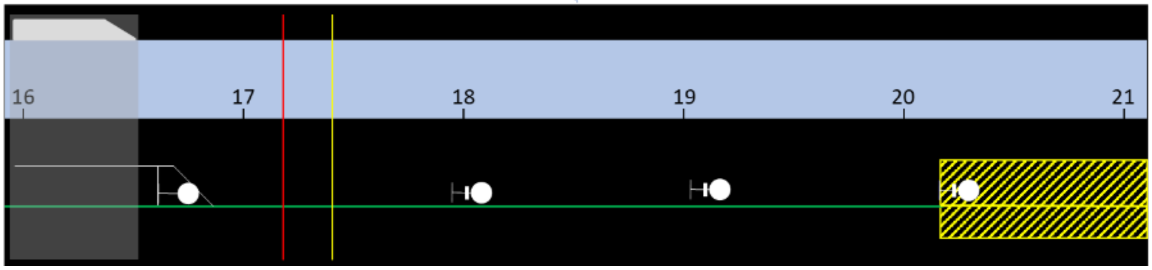


Figure 10. Onboard Display in EO-PTC

The rest of the signal status codes are utilized without modification. All PTC states and enforcements (other than for the Approach and Advance Approach aspects) remain unchanged for EO-PTC. This includes switching states and enforcements of mandatory directives.

The dependency on the track database allows for incremental deployment of EO-PTC on a per-territory or per-signal basis, as determined by the operating railroad. Thus, a PTC train could use EO-PTC in some or eventually all PTC territory.

2.3.1 Expected Benefit Example

2.3.1.1 Following Moves

EO-PTC following moves are handled similarly to current Overlay PTC operations in that train separation is achieved through block signaling and a train is not allowed to enter an occupied block without a Restricted Speed Restriction. However, speed reductions required by Approach and Advance Approach indications are no longer required. Trains separated by at least one block length can improve efficiency of movement by traveling at the speed of the leading train while maintaining a shorter safe following distance. The result is reduced headway (which can translate to increased capacity) within EO-PTC territory.

This efficiency gain remains true as long as a following train paces itself such that the leading train clears each block before the following train gets within braking distance (or warning distance, depending upon crew training) from that block. The enhancement of EO-PTC not only reduces headway in following moves but also during recovery from service disruption scenarios.

2.3.1.2 Sidings and Crossings

When two trains meet nearly simultaneously at a siding to pass in opposing directions as illustrated in Figure 11, Train 2, which is travelling on the main track, will potentially be able to continue at a higher speed, leveraging the EO-PTC capabilities. The entrance to the main track is still governed by an Approach signal, but Train 2 may now maintain its speed, as opposed to reducing speed due to a premature speed restriction imposed by Overlay PTC. If Train 2 does not reach its braking curve limit by the time Train 1 clears the track circuit of the switch, it will be able to continue without reducing speed (Figure 12), improving movement efficiency in this and other similar scenarios.

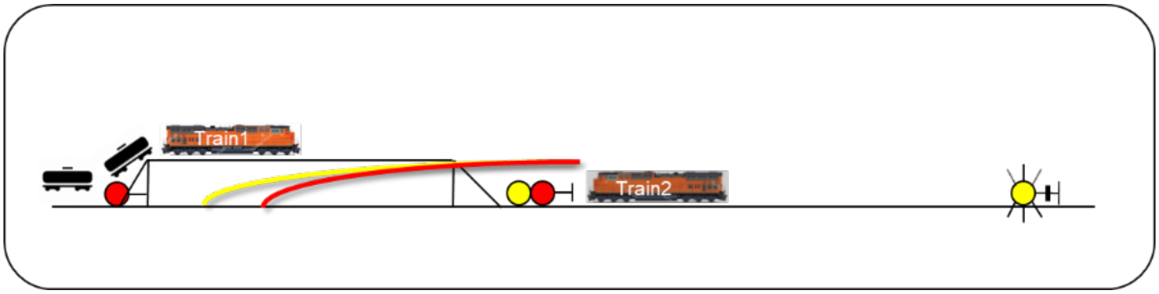


Figure 11. Near-Simultaneous Siding Meet

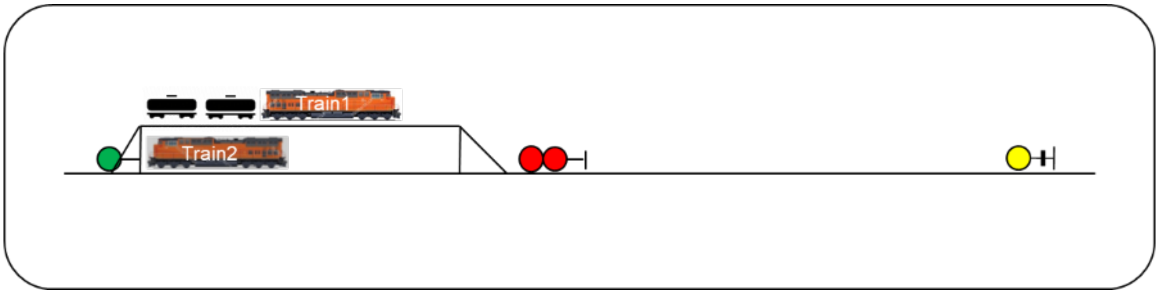


Figure 12. In EO-PTC, Train 2 Continues without Reducing Speed

When two trains meet at a diamond crossing, the train approaching the occupied crossing will not have to reduce speed according to signal indications. Instead, it will continue according to the braking curve. If the occupying train clears the crossing before the approaching train reaches the limits of its braking curve, it can continue without reducing speed.

2.3.1.3 Service Disruption Recovery

One of the key potential advantages of EO-PTC as compared with Overlay PTC is the faster recovery from service disruptions. Service disruptions result in trains having to completely stop or move through a track block that has had its effective speed limit temporarily reduced from normal track speed to; e.g., Restricted Speed.

There are multiple potential causes for this scenario, such as a failed WIU, Temporary Speed Restriction, Work Authority, track being out of service due to maintenance, etc. The ability to follow a train ahead more closely that is also resuming normal operation after the disruption will result in faster recovery from said disruptions once they have been resolved or when trains are leaving the disrupted area.

Multiple trains attempting to enter mainline track from a yard will benefit from a similar efficiency gain.

2.4 Quasi-Moving Block

2.4.1 Overview of QMB Concept

The general concept of QMB is that the Computer-Aided Dispatch (CAD) system will create and modify routes that are checked by a centralized interlocking system. Once a route is accepted, the back office system creates or updates a train's PTCEA (its exclusive authority), checking that it does not overlap any other PTCEA. The PTCEA is then issued to the train through the available communication path(s). The train onboard segment sets its target limits and speeds based on the PTCEA received from the back office and other information. As the train moves, the onboard continuously monitors the status of field devices broadcast from WIU locations to verify that they are still consistent with its PTCEA. The train rolls up its PTCEA based on the calculated or detected end-of-train location and informs the back office, which can then extend a PTCEA for a following train.

2.4.2 Justification for QMB

QMB is part of a strategic plan to provide higher reliability and capacity train control. It can provide benefits in reliability, safety, and capacity as seen in Table 2. These benefits come at the cost of some architectural changes, including new back office functions that implement interlocking functionality and PTCEA management, additional vital functions in the onboard segment, optional vital end-of-train location determination and optional detection of broken rail within an occupied block.

Table 2. QMB Expected Benefits

Category	Expected Benefit
Safety	Collision protection at all speeds (including restricted speed); vital when using end-of-train location determination.
	Pull-apart protection applies in any event when the reported vital end-of-train indicates greater train length than estimated, in which the pulled-apart cars are protected by a PTCEA.
	Loss-of-shunt protection (using movement authorities, train location reports, and train length data as additional sources of occupancy detection)
	Uniform method of train control using PTCEAs for all trains.
	Verification that crew track selection matches authorized tracks included in train's movement authority (note: this may already be done to some extent in some PTC implementations).
Capacity and Efficiency	Increased capacity beyond that of EO-PTC if track circuits are shortened. Shorter track circuit blocks are more practical with QMB because: a) there is no need for additional aspects since the signal heads and associated aspects are eliminated, and b) the cost of additional track circuits is reduced because the wayside logic and WIU functionality are minimal.
	Increased capacity beyond that of EO-PTC if next generation track circuits that can provide broken rail protection within an occupied block are used. Vital EOT location must be used in conjunction with broken rail detection in an occupied block, such that the following train may enter an occupied track circuit at MAS and maintain MAS up to braking distance from the last reported location of the end of the train ahead at the time the following train entered the block.

Category	Expected Benefit
	QMB provides a key migration step toward FMB, since alternative broken rail and rollout detection is all that must be added to migrate from QMB with PTL-EOT to FMB (along with software changes).
	QMB can reduce delays caused by approach and time locking. When a dispatcher needs to change a route already assigned to a train and the train's braking curve indicates the train can stop before the interlocking, then the route can be changed without time penalty.
Reliability-Maintainability	Simplifies and reduces field components (such as field logic devices, cabling, etc.) and facilitates diagnostics and maintenance
	Facilitates removal of signal heads

2.4.3 QMB Core Principles

The QMB method of train control is based on several core principles:

- Train authority is granted exclusively in the form of non-overlapping and electronically delivered movement authorities or segments thereof (PTCEAs).
  - Every train or other rail vehicle on controlled mainline track must have a PTCEA (with the possible temporary exception of work gangs and equipment operating under Track Bulletin Form B that have not yet been PTC equipped).
  - Control of PTCEAs is centralized in the QMB office, which is responsible for extending train PTCEAs and ensuring that they do not overlap.
  - Trains are responsible for initiating roll-up of their own PTCEAs.
  - The PTC onboard segment will determine its end-of-train location at the time its PTCEA is to be rolled up, which may be in a vital manner (if based on reports from PTL-EOT) or a non-vital manner.
- The PTC onboard determines and enforces speed limit, based on the most restrictive of PTCEA speed limit, train-specific speed restriction (where applicable), and track speed restrictions, both permanent and temporary. In addition, it also limits speed according to the braking curve as in EO-PTC when approaching a Stop, Stop and Proceed or Restricting target.
- Retention of WIU-to-locomotive peer-to-peer communication for a binary clear/not clear report from each track circuit.
- Many vital functions currently implemented in a distributed manner with field equipment can be centralized, allowing for lifecycle cost savings.
  - Interlocking logic can be centralized, allowing for the removal of components related to field interlocking (centralization of interlocking logic can be done initially, or at a later stage, after the PTCEA functionality has been operational for some time).
  - Wayside signals and associated signal logic can be removed.

2.4.4 QMB System Architecture

QMB inherits most of the Overlay PTC architecture and design. The onboard retains all the existing core functionality of the Overlay PTC system. The onboard also continues to obtain the status of field devices from Wayside Status Messages (WSMs) generated by WIUs. The BOS continues to be the interface between the back office and the field. Figure 13 illustrates the overall QMB architecture.

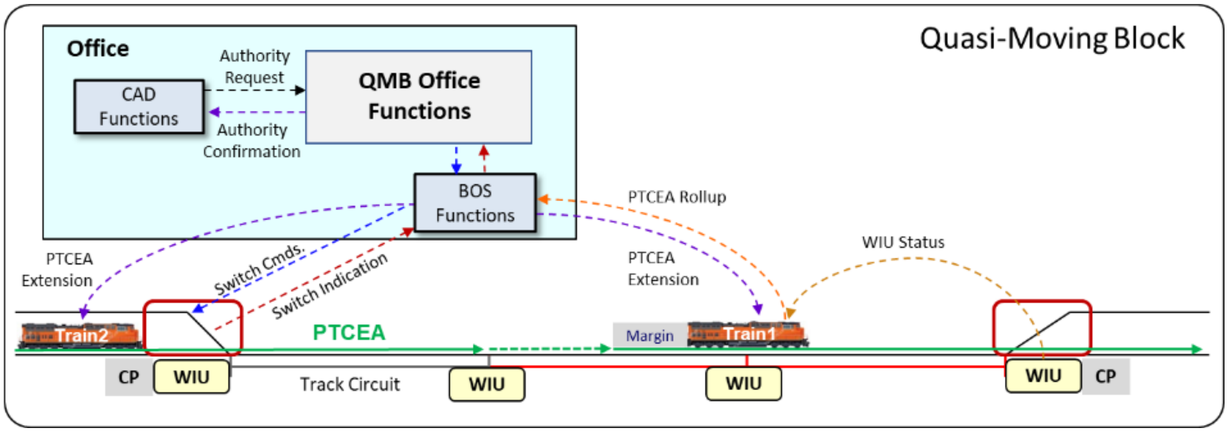


Figure 13. QMB Architecture Diagram

The onboard requires new functions to determine the end-of-train location and to roll up its own PTCEA. The end-of-train determination will include a safety margin to account for the level of accuracy of the location determination system.

QMB also introduces a new functional component – the QMB office – responsible for controlling the issuance of all PTCEAs in the system. It keeps track of what PTCEAs have been issued and what PTCEA roll-ups/extensions have occurred, keeping a vital record of what segments of track are reserved for trains and what segments of track are available for use. It also requires vital centralized interlocking functions, verifying that requested PTCEAs are safe to issue, consistent with the current route status. It communicates with field devices (switches and track circuits) via existing (PTC) communications paths to acquire their status and to issue commands.

In QMB, routes through and between control points can be managed by and maintained in the centralized interlocking functionality. Field wayside signals at intermediates and control points can be removed, as PTCEAs and WSMs are communicated via data radio to the onboard. PTCEAs provide the authority for train movements and track occupancy, and the onboard determines speed and authority limit targets based on PTCEAs, WSMs, train-specific speed restriction (where applicable), and track speed restrictions, both permanent and temporary.

The QMB office interfaces with the CAD system that the railroad uses to dispatch trains. Through this interface, QMB receives train authority requests, including signaling route requests and special authorities (such as track and time, track permit and reverse movements). It also uses this interface to command switches in the field to the correct alignment and issue PTCEAs to trains. It is expected that minimal changes are required to existing CAD systems.

2.4.5 QMB System Interfaces

PTC segment interfaces are slightly modified in QMB as compared to Overlay PTC to accommodate the required modifications for the QMB architecture. Figure 14 depicts the interfaces among PTC segments and external components.

Notice the following:

1. It is assumed that the existing BOS and Wayside Status Relay Service (WSRS) server, along with their interfaces, remain unchanged.
    a. It is assumed that the WSRS server contains the latest WSM updates from all WIUs controlled by a railroad.
2. The existing distributed field interlocking logic can optionally be replaced by simplified localized field electronics for monitoring field component status and for actuating switches at control points.
3. The QMB office interfaces with WIUs using existing PTC communication paths (e.g., 220 MHz radios) and a vital protocol; i.e., the traditional interface between the CAD system and field interlocking (code lines) is not used.

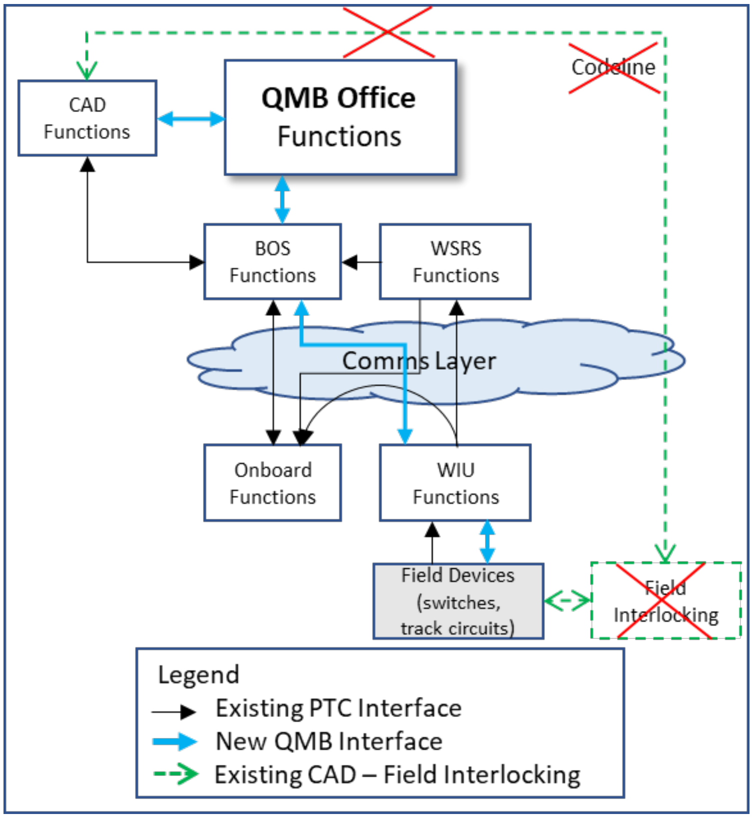


Figure 14. QMB Interfaces Schematic Overview

2.5 Full-Moving Block

While various intermediate steps and other aspects of train control with incremental ROI will be addressed, for the scope this project, the target end state is envisioned to be a standalone FMB method of train control operation. Key potential operational advantages of FMB as compared with Overlay PTC are increased capacity via reduced headways for line of road operations (see Figure 15), fewer premature warnings/enforcements, and faster recovery from service disruptions. FMB also offers a potential means to further reduce the amount of vital wayside hardware needed (i.e., track circuits, since a suitable alternative means of broken rail detection is required for FMB) and therefore a means to increase overall system reliability and safety effectiveness. An additional benefit of shifting functionality from the wayside to the back office is providing better diagnostics to the back office. A safety benefit of FMB train control is the ability to prevent train collisions at restricted speed, which is also the case when operating with QMB with PTL-EOT.

FMB operation is an enhancement to PTC; thus, anywhere it is used will be PTC territory. Any trains not equipped for FMB would operate in the territory in fixed block mode or QMB mode, with correspondingly longer headways associated with them.

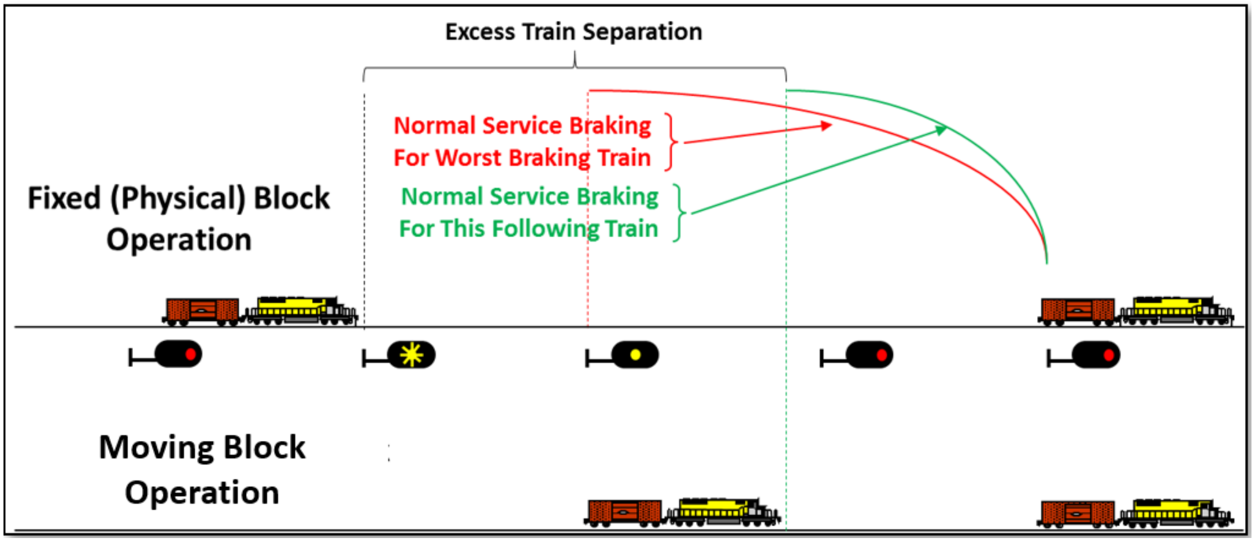


Figure 15. Fixed Physical Signaling Blocks Impose Artificial Constraints, Resulting in Excess Train Separation and Reduced Line-of-Road Track Capacity

For the purposes of this document, FMB operation is defined as one in which movement authority can be issued up to the last reported rear location of the train ahead (versus issuing only to the boundary of the last block the train occupies), and exclusive movement authority (PTCEA) is conveyed to each train as a message containing a single From and To limit. When not in dark territory, broken rail and rollout detection may be used in formulating each movement authority message or may be conveyed to the train separately.

The overall architecture of FMB is equivalent to the architecture of QMB, as it is founded on the principle of PTCEAs being issued from the back office to trains. The main differences are based on the fact that FMB does not require track circuits for train location determination nor for broken rail and rollout detection. Figure 16 illustrates the overall architecture of the FMB train control method, depicting its main components and interfaces.

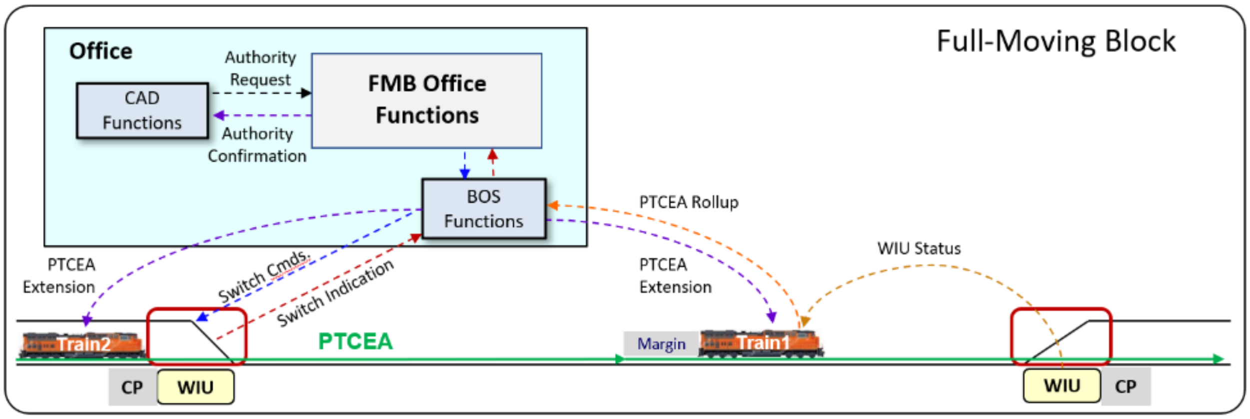


Figure 16. FMB Method – Overall Architecture Diagram

To achieve operational benefits, FMB train control requires more precise and timely train location information than what is provided by conventional track circuits. Such information may be provided by an onboard location determination system that frequently transmits location reports for the front and rear of the train.

Shorter headways can be achieved because a following train's exclusive movement authority can be advanced as soon as there is positive determination that the train ahead has cleared a segment of track and has automatically truncated its authority behind it, rather than having to wait until an entire track circuit block has been vacated. Theoretically, train separation under FMB control could be reduced to the instantaneous braking distance of the following train. However, limited location report update rates – typically due to limited Radio Frequency (RF) bandwidth, location determination inaccuracies (front and rear of train), braking distance uncertainty, enforcement warning time, and uncertainty in location of detected rail breaks – require that some margin be added to the train separation in a practical implementation.

FMB train control requires a fail-safe means to ensure that all trains operating in the territory are located. Specifically, there must be a means to assure there is no unidentified train (that may not be communicating for a variety of potential reasons) between two communicating trains. This assurance is provided by a Safety Server function that keeps track of all train locations from the time a train is dispatched, or its PTC system is initialized until it is terminated (or at least from when it enters until it leaves PTC territory).

2.6 Centralized Interlocking

Conventional CTC systems interface with vital interlocking functions having fail-safe components installed along the track, varying from older relay-based to modern microprocessor-based systems. A conventional trackside interlocking architecture is illustrated in Figure 17. Track circuits provide occupancy status of block segments while wayside signals convey movement authorization to trains. Requests originated from the Dispatching System are processed in the field at control points and the status of field components is reported back. The interlocking also locally controls the position of switches and determines the aspects shown on signals at control points. CTC systems obtain train presence information from track circuits and provide authority with wayside signals; they do not consider the train as an explicit component of the control system, but rather as an external component.

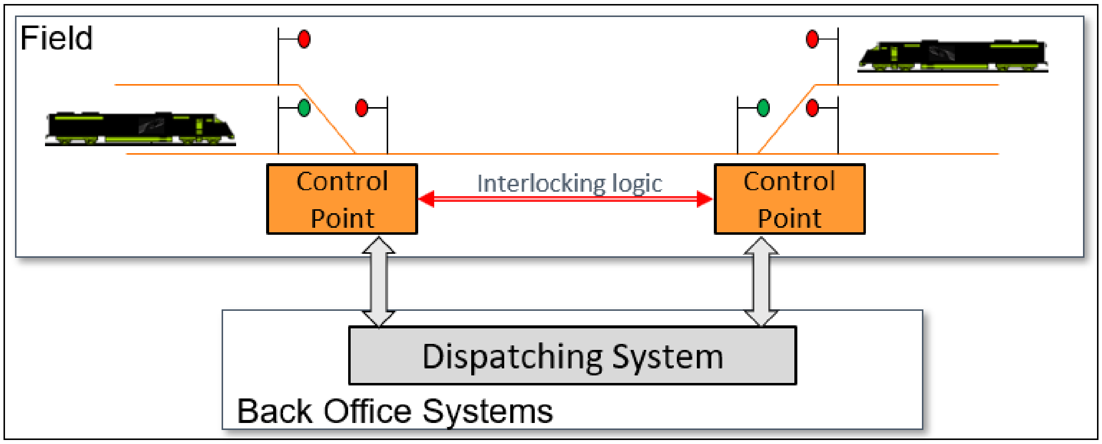


Figure 17. Conventional Field Interlocking Architecture Schematic

In a centralized architecture, the vital interlocking logic conventionally implemented in the field is reallocated to central computers, as illustrated in Figure 18, which reduces the complexity of vital components in the field and provides benefits related to maintenance and reliability.

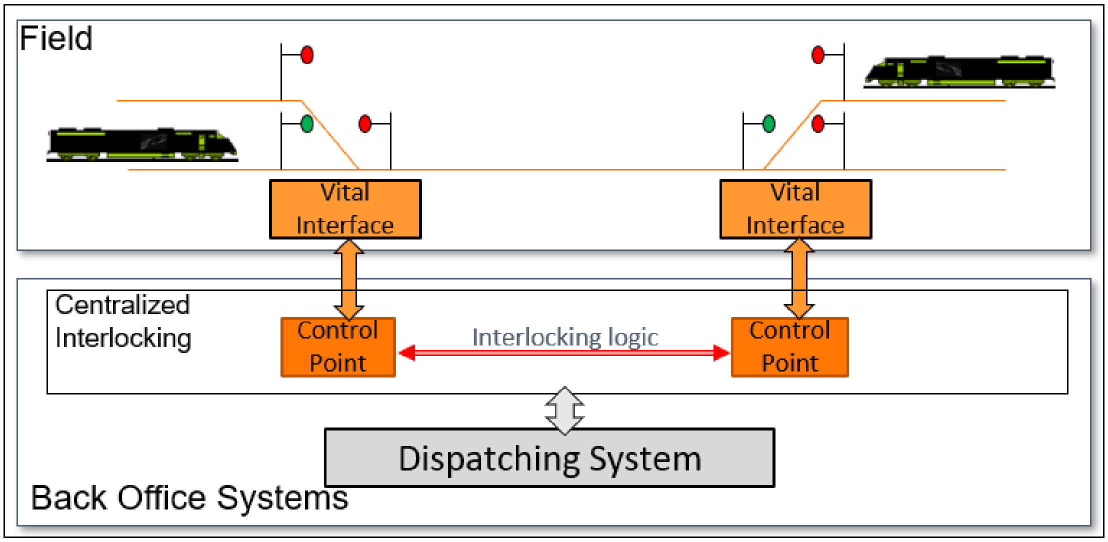


Figure 18. CTC with Centralized Interlocking Architecture

With the advent of PTC, trains have become an active component of the train control system, and QMB and FMB are designed to take advantage of that by sending movement authorities containing vital route information to and receiving status directly from trains. This allows the interlocking logic to be designed in a more flexible and possibly simpler way – wayside signals are removed as trains can receive authority on board and trains can directly respond to route commands that affect interlocking functions, such as route canceling. This means that QMB and FMB make a more compelling case for the centralized interlocking design when compared with a conventional distributed system. Figure 19 illustrates QMB/FMB with a centralized interlocking architecture, where the QMB/FMB office functions interact with trains to send movement authorities and receive train updates. The QMB/FMB office functions interact or integrate with the centralized interlocking segment to validate movement authorities and command the field devices and receive their status.

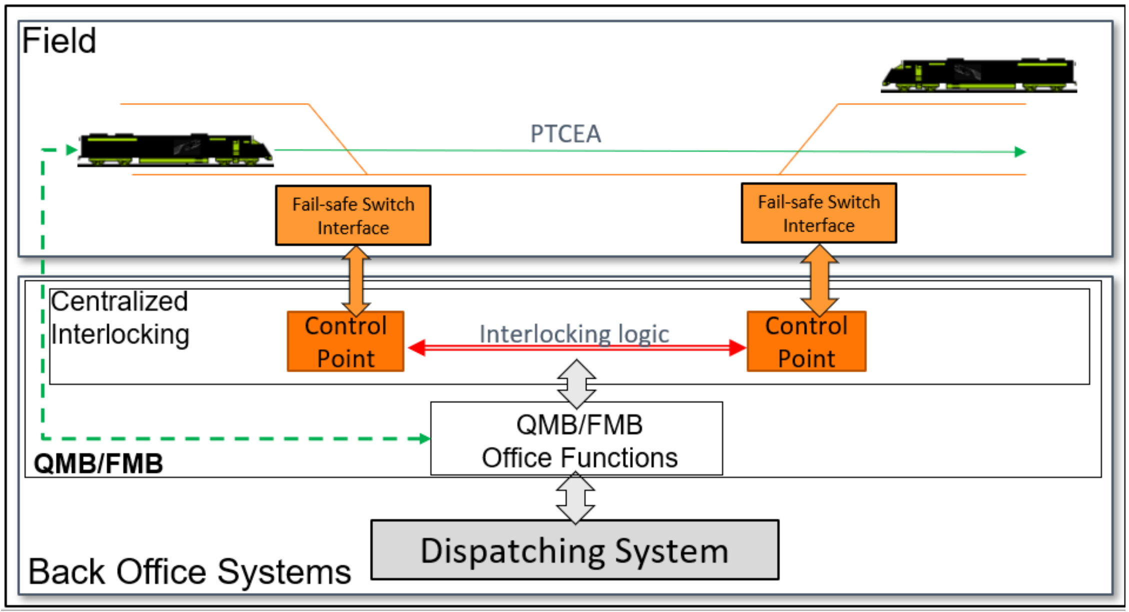


Figure 19. QMB/FMB with Centralized Interlocking Architecture

Combined, the benefits of having a simplified field configuration and the integration of trains in the overall train control design, a centralized interlocking design provides the following benefits:

- Reduced maintenance costs due to the elimination of components (such as cabling, signals, and field logic components) and use of lower cost, non-vital components in the field
- Easier configuration and maintenance procedures (since components are office-based rather than field-based)
- Potentially higher reliability due to reduction of functions implemented in the field and higher availability components in the back office.
- Potentially simpler and more flexible interlocking logic
- Potential to increase capacity with the elimination and/or optimization of constraints included in field interlocking design, such as time-locking for route cancelling requests.
- Facilitates the implementation of "driver control" in which dispatcher allows a designated interlocking to accept requests from a specified train.

3. HRCTC Performance Analysis and Results

The performance of train control methods was assessed in two ways:

1. Ability to recover from the negative impacts of Overlay PTC: TTCI analyzed whether the proposed train control methods would be able to compensate for the negative impacts in railroad operations caused by the introduction of Overlay PTC. To estimate that ability, TTCI ran railroad network simulations and calculated the total train travel times for each of the train control methods. The results were compared to a baseline case of train operations without PTC.
2. Capacity increase in railroad operation: TTCI also estimated the operational capacity gains and headway reduction for each of the proposed HRCTC methods. This analysis was developed in two ways: 1) with analytical calculations to estimate the theoretical maximum gains; and 2) with results of railroad network simulation that provides results closer to actual railroad operation as opposed to maximum theoretical estimation.

The following sub-sections describe the methodologies, input data and configuration parameters used to develop each of the performance analyses, and the results obtained.

3.1 Methodology to Analyze the Ability to Recover from Overlay PTC

TTCI developed a methodology to analyze whether the proposed HRCTC methods can compensate for the negative impacts in train operation introduced by Overlay PTC method. As stated in Section 2.2, Overlay PTC introduces operational impacts on railroad operation due to multiple causes that can be summarized in two main groups, related to:

- The conservatism of the PTC enforcement braking algorithm
- The occurrence of PTCIEs; i.e., failure of PTC components (hardware and software) and human errors when operating the PTC system.

Potential gains that can be achieved with the proposed HRCTC methods due to higher reliability and availability of underlying systems (e.g., decommissioning of field signals and/or replacement of field interlocking with Centralized Interlocking) were not included in this analysis. Those can potentially further increase the gains obtained with advanced train control methods such as QMB and FMB.

The following steps describe the process followed by TTCI to estimate the performance of the train control methods:

1. For pre-determined railroad operational scenarios, TTCI ran railroad network simulations without PTC operation (non-PTC case); i.e., the operational conditions before the introduction of PTC, and calculated the total train travel times. These simulations produced the baseline reference for the comparison with the PTC methods.
2. For the same operational scenarios, TTCI simulated the network operation including only the conservatism of the PTC braking enforcement algorithm when trains had to reduce speed due to PTC speed targets, which produced the estimation of the negative operational impact of the PTC braking algorithm when comparing the results with the baseline.

3. Next, TTCI introduced the PTCIEs in the network simulations, which caused additional delay to train operations. The combination of the train delays caused by the conservatism of the PTC braking enforcement algorithm and the PTCIEs produced the overall negative operational impact (expressed as train delay) of Overlay PTC when compared to the baseline.
4. As a final step, TTCI ran the same operational scenarios, repeated steps 2 and 3 for each of the proposed HRCTC methods (namely EO-PTC, QMB and FMB), and calculated the train delays for comparison with the baseline.

Figure 20 illustrates the concept applied by TTCI to generate the comparison performance among the train control methods. (Note that in this figure, the relative train travel time for each method indicated along the dependent axis does not correlate with the actual results of the analysis and are only shown here as an example of the methodology employed.)

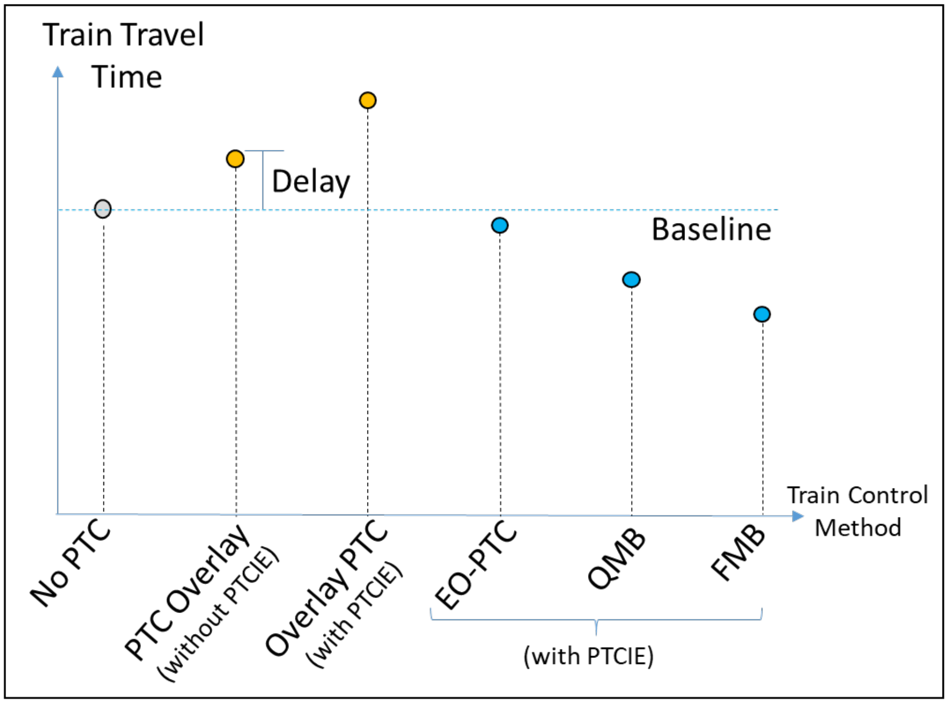
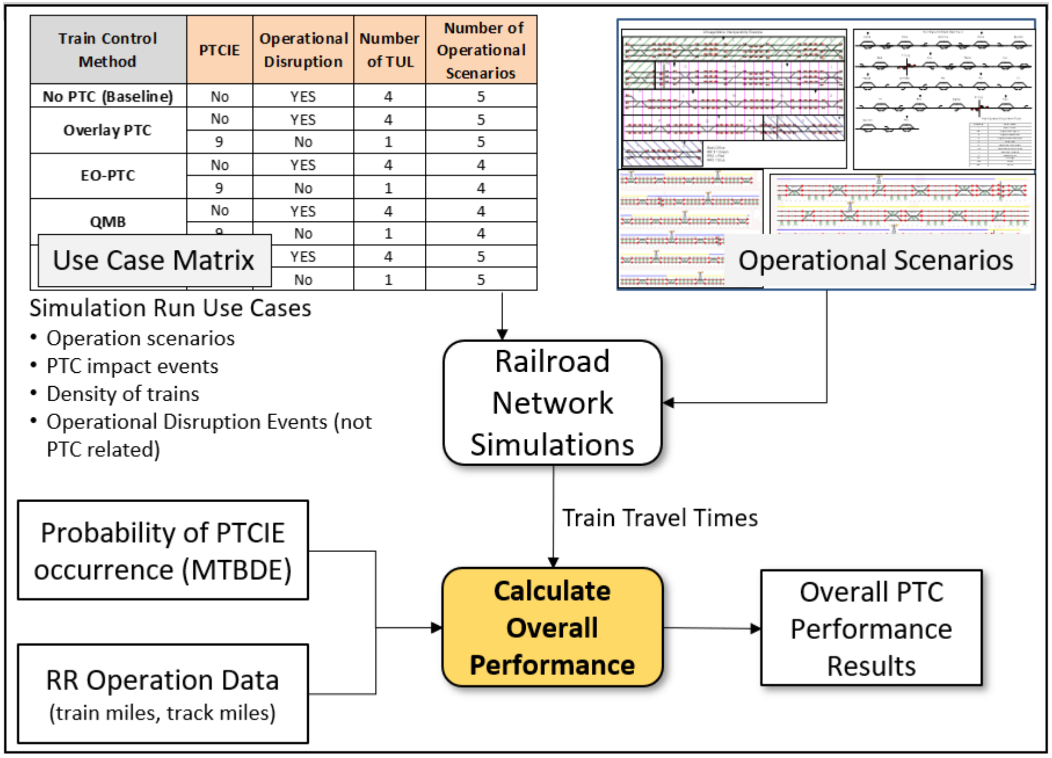


Figure 20. Train Travel Time Comparison among Train Control Methods

The estimation of the total travel times for each train control method included the use of multiple tools to simulate railroad network operation, compilation of results from simulations, calculation of overall results, and analysis.

Figure 21 illustrates the performance analysis process macro flow developed by TTCI for this project.



Train Control Method	PTCIE	Operational Disruption	Number of TUL	Number of Operational Scenarios
No PTC (Baseline)	No	YES	4	5
Overlay PTC	No	YES	4	5
	9	No	1	5
EO-PTC	No	YES	4	4
	9	No	1	4
QMB	No	YES	4	4
	[illegible]	No	1	4
[illegible]	[illegible]	YES	4	5
	[illegible]	No	1	5

Figure 21. TTCI's PTC Performance Analysis Process Macro Flow Diagram

The steps and tools used by TTCI as illustrated in Figure 21 are described below:

1. **Selection of operational scenarios and details:** Five operational scenarios, including signaled single-track, double-track and triple-track, non-signaled territory, and DUA, were selected. Details of each operational scenario, such as train schedules, train consist, track characteristics, and others, were defined jointly with the participating railroads.
2. **Definition of use cases:** TTCI prepared a list of simulation runs required to develop the performance analysis results. The list, identified as the Use Case Matrix, contains the combination of simulation run cases describing the combination of parameters for each case, such as type of operational scenario, density of trains, PTCIE, and operational disruption events.
3. **Configuration of the network simulation tool:** TTCI configured the railroad network simulation tool per the Use Case Matrix, ran the simulations, and gathered the total train travel times obtained from each use case run.
4. **Compilation of the results:** The use case results were compiled for each type of analysis being prepared. TTCI used two additional information sources that, combined with the total train travel times, produced the overall performance results:
    a. The MTBDE of the PTCIE, which defines how frequently a PTCIE is expected to occur.
    b. The total train track mileage and train miles operated per type of operational scenario, used to calculate average weighted results and produce overall and nationwide results.

3.1.1 Configuration Parameters Used in Network Simulations

TTCI used Rail Traffic Controller™ (RTC), a railroad network simulation tool from Berkeley Simulation Software (BSS), to simulate railroad network operations and calculate train travel times for the operational scenarios selected for this project. RTC is a widely used railroad network simulation tool used by North American railroads. Its models and configuration parameters have been extensively improved and validated by its users over many years.

TTCI created RTC models for five operational scenarios that include signaled single-track, signaled double-track, signaled triple-track, non-signaled territory, and dense urban area (DUA). Each RTC model was configured with typical operational parameters including train schedules, train consist, and track layout. Details of each operational scenario are included in Appendix A.

TTCI prepared requirements for the necessary additional capabilities to model PTC operation and provided them to BSS and FRA for implementation in their respective railroad network simulation tools. The requirements included features to simulate the conservatism of the PTC braking enforcement algorithm, the operational principles of each type of train control method, and the impact caused to train operations due to the occurrence of PTCIE. TTCI worked extensively with BSS to test and validate the PTC features developed in RTC. Details of the PTC simulation requirements prepared by TTCI are included in Appendix G.

The negative impacts or positive gains obtained under each train control method depend on the density of trains operating in the network, as each train control method allows for different minimum headway, as well as the indirect impact to trains caused by PTCIEs, such as when a train stops or reduces speed due to a failure of a PTC component that causes trains behind and sometimes trains in the opposite direction to also reduce speed or stop. TTCI ran RTC simulations at selected train density levels, identified as Track Utilization Levels (TUL), to assess the performance of each train control method as train density varies. TTCI used four TULs as a percentage – 25, 50, 75, and 100 percent – of the maximum practical capacity of each operational scenario. Appendix B describes the details of the calculation of the TULs used in this analysis.

TTCI also ran RTC simulations, introducing typical operational disruption events not related to PTC operation – such as track outage for maintenance and repair. The simulation results were used to assess the ability of the proposed train control methods to better recover from those types of events. Section 3.1.6 describes the details of the operational disruption scenarios used for this analysis.

TTCI ran several RTC simulations combining the above described configuration parameters, as shown in Table 3.

Table 3. Simulation Use Case Matrix

Train Control Method	PTCIE	Operational Disruption	Number of TUL	Number of Operational Scenarios
No PTC (Baseline)	No	YES	4	5
Overlay PTC	No	YES	4	5
	9	No	1	5
EO-PTC	No	YES	4	4
	9	No	1	4
QMB	No	YES	4	4
	9	No	1	4
FMB	No	YES	4	5
	9	No	1	5

QMB can be implemented using current track circuits, with shorter track circuits, with NGTC, or potentially other broken rail detection technology. Due to limitations in simulation time and capabilities, this project looked only at half-length track circuits, considering that configuration to be representative of the type of improvement possible with QMB, and recognizing that the actual improvements may be different if NGTC or other methods are used.

3.1.2 Train Delay Calculation

TTCI used the train travel times from the RTC simulations as the core data to calculate the performance of the train control methods.

For a given case within the Use Case Matrix, RTC simulation runs were executed and the total travel time (arrival time at destination minus departure time at origin) of all trains in the simulation was accumulated, generating the total travel time for the case, as expressed in:

$$TravelTime(Case) = \sum_{i=1}^{N_{Trains}} ArrivalTrain(i) - DepartureTrain(i) \qquad (1)$$

Where N_{Trains} is the total number of trains in the simulation. The total delay for a train control method (TC) was calculated by comparing the total train travel time of that train control method with the baseline (no PTC) for the same case configuration parameters, as expressed in:

$$TrainDelay(TC, Case) = TravelTime(TC, Case) - TravelTime(Baseline, Case) \qquad (2)$$

The total miles operated by all trains in the simulation was also accumulated, generating the total train miles operated for that case. The average delay per train mile was calculated by dividing the total train delay by the total train miles of that case, as expressed in:

$$DelayperMile(TC, Case) = TrainDelay(TC, Case)/TotalMiles(Case) \qquad (3)$$

TTCI also combined the train delay calculations of the five operational scenarios to generate the overall train delay for each of the train control methods. This was done by weighting the train delay calculation with the proportion of total train miles operated over a period of time for each of the operational scenarios (OS), as expressed in:

$$TotalTrainDelay(TC) = \sum_{i=1}^{5} TrainDelay\big(TC, OS(i)\big) * ProportionMilesOS(i) \qquad (4)$$

Where:

$$ProportionMilesOS(i) = \frac{TotalMilesOS(i)}{TotalMilesAllOS} \qquad (5)$$

3.1.3 Operational Scenario and Nationwide Performance Extrapolation

TTCI used the total PTC train miles (i.e., total train miles operated in territories where PTC is required) per operational scenario provided by three Class I railroads for 1 year of operation to calculate the proportion of total train miles for each operational scenario compared to the total train miles of all operational scenarios combined. The proportions were used to aggregate the train delay calculations for a train control method, as explained in Section 3.1.2.

As the total PTC train miles was not available for all railroads nationwide, TTCI extrapolated the total train miles based on the data provided by the three Class I railroads to nationwide figures to estimate total nationwide train travel time delays. TTCI used the total PTC route miles provided in FRA's dashboard [1], by extrapolating the total PTC train miles from the three Class I railroads to the proportion of PTC route miles between the three Class I railroads and the total route miles nationwide, as shown in Table 4.

Table 4. Total PTC Route Miles from the FRA PTC Dashboard

FRA PTC Dashboard		
PTC Route Miles	All Railroads	**58,436**
	3 Class 1 RRs	**38,365**

Table 5 shows the total train miles operated in 1 year for each operational scenario, their proportion compared to the total train miles operated in all operational scenarios, and the nationwide extrapolation of total train miles using the FRA PTC Dashboard route miles data.

Table 5. Percentage of Train Miles per Operational Scenario and Nationwide Extrapolation

Operational Scenario	Percentage	Total Annual Train-miles	
		3 Class 1 RRs	**Nationwide**
Non-signaled	3%	8,233,163	**12,540,418**
Signaled Single Track	42%	127,481,071	**194,173,957**
Signaled Double Track	41%	126,537,651	**192,736,979**
Signaled Triple Track	3%	8,446,029	**12,864,645**
DUA	11%	34,593,764	**52,691,808**
TOTAL	100%	305,291,679	**465,007,808**

3.1.4 Operational Impact of the PTC Braking Algorithm

Three types of train braking operation were modeled to simulate the operation of PTC:

1. Full-service application: Used to decelerate a train for an enforcement, such as when the PTC onboard hardware fails.
2. Normal service application without PTC target: Used by the crew to decelerate at targets that are not PTC enforced, such as when a passenger train stops at a station.
3. Normal service application with PTC target: Used by the crew to decelerate to comply to PTC enforced targets, such as a Stop signal or a Speed Restriction.

Figure 22 illustrates the braking curves of the three types of PTC braking operation.

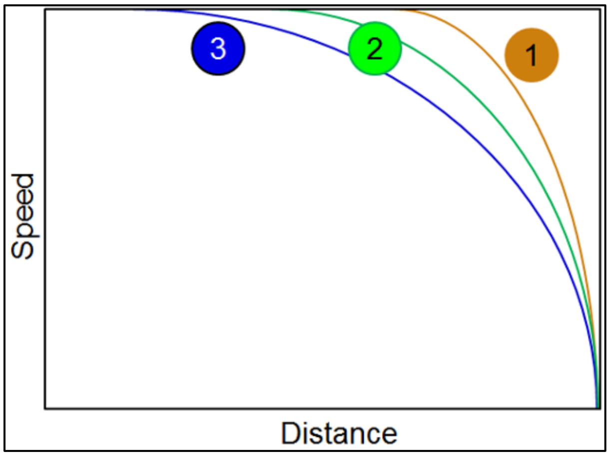


Figure 22. Train Braking Curves

As indicated in Figure 22, the train braking deceleration rate when the train engineer is reducing speed to a non-PTC target (curve 2) is less than the full-service braking application (curve 1). Assuming that the PTC braking enforcement algorithm includes conservatism, including the engineer's reaction to PTC warning time, researchers expected that the PTC target braking rate (curve 3) is less than the non-PTC target braking rate (curve 2).

RTC already has braking rates configured for the full-service application (curve 1) and for the non-PTC braking application (curve 2) for multiple train classes, and those were used in the simulation runs developed for this project.

TTCI estimated the PTC target braking rates (curve 3) based on simulations using TTCI's Train Operation and Energy Simulator™ (TOES) and the PTC braking enforcement algorithm currently in use by the Class I railroads. TTCI ran multiple simulations with various train and track characteristics simulating the braking performance of the onboard PTC braking algorithm. Based on the results of the simulations, TTCI calculated average PTC target braking rates for selected train classes. Appendix D contains the details of the PTC braking rate simulations and calculations.

TTCI calculated the operational impact introduced by the conservatism of the PTC braking algorithm by running RTC simulations for the same scenario twice and comparing the train travel times for each case:

- Non-PTC case: Trains were configured with non-PTC target braking rates for signal indication and speed restriction targets.
- PTC case: Trains were configured with PTC target braking rates for signal and speed restriction targets.

Table 6 shows the braking rates used in RTC simulations for the different train classes.

Table 6. PTC Target Train Braking Rates Used in RTC Simulations

Train Class	Braking Rates (MPH/s)	
	Non-PTC Target	PTC Target
Expedited	0.6	0.32
Freight	0.5	0.29
Passenger	1.5	1.06

3.1.5 PTC Impact Events and RAM Parameters

TTCI used RTC simulations to estimate the operational impacts caused in a railroad network due to the occurrence of PTCIEs (failure of PTC components, hardware and software, and human errors when operating the PTC system). TTCI configured cases where those events were triggered during RTC simulation and measured the train delays as explained in Section 3.1.2.

TTCI ran RTC simulations separately for each type of PTCIE, configuring the occurrence of the event and the time for the recovery from the event, identified as Mean Time to Recover (MTTR). TTCI ran multiple RTC runs for each PTCIE case, according the following specifications:

- At five different locations in the operational scenario
- At six different times during the day
- With 20 different simulation seed numbers (that cause each run to have variable train departure times, based on the configuration of train departure variance)

The results of the 600 simulations were compiled and analyzed and average train delay results were calculated ($\mathrm{PTCIE}_{\mathrm{TrainDelay}}$).

TTCI used the PTCIE's MTBDE to calculate the total train delay per train mile of a PTCIE. TTCI first calculated the probability of occurrence of one PTCIE over one year of operation by dividing the total hours in one year by the MTBDE, as shown in:

$$\mathrm{PTCIE}_{\mathrm{Occurrence}} = \mathrm{Hours}_{\mathrm{Year}} / \mathrm{PTCIE}_{\mathrm{MTBDE}} \qquad (6)$$

For events related to PTC components with multiple occurrences in a scenario, such as a WIU, TTCI multiplied the $\mathrm{PTCIE}_{\mathrm{Occurrence}}$ by the number of those components in a scenario.

From the RTC simulation, TTCI calculated the total train miles operated in 1 year for a use case simulation (TotalTrainMiles).

The final calculation of the total train delay per train mile caused by a PTCIE is shown in:

$$\mathrm{PTCIE}_{\mathrm{DelayperMile}} = \mathrm{PTCIE}_{\mathrm{Occurrence}} * \mathrm{PTCIE}_{\mathrm{TrainDelay}} / \mathrm{TotalTrainMiles} \qquad (7)$$

The PTCIE simulation included events that occurred at terminal prior to train departure and en route, i.e., after train departure from terminal. Table 7 shows the list of PTCIEs included in the Use Cases and the description of their impact on operation.

Table 7. List of PTC Impact Events Included in Use Cases

Type	PTC Impact Event	Description	Operational Impact
Terminal	Initialization Delay	Issues during initialization for multiple reasons (user error, onboard failure, etc.) that cause train delay.	Train is delayed at departure until problem is resolved.
	Onboard Hardware Failure – Replace Locomotive	Onboard hardware failure non-recoverable that requires replacement of lead locomotive.	Train is delayed at departure until lead locomotive is replaced.
En route	PTC Wayside Failure	Failure of a wayside component that prevents a train from receiving a WSM from a WIU.	Depending on the type of WIU, trains stop or reduce speed and operate at RSR through next block.
	Onboard Hardware Non-Recoverable	Failure of onboard hardware that is non-recoverable.	Train is enforced, onboard PTC system is cut out, and train resumes in Reduced speed.
	Onboard Software Recoverable	Failure of onboard software that is recoverable after reboot.	Train is enforced, onboard PTC system is rebooted, and train resumes at Normal speed.
	BOS-Loco Link*	Failure of BOS-loco link that prevents locomotive from communicating with back-office.	Depending on the type of communication backbone and size of gaps, trains may disengage (at WIUs with radios) or not receive a WSM (WSRS territory).
	Back Office Downtime	Back office downtime due to failure or maintenance	Trains operating in the territory controlled by the back office disengage PTC after timeout and resume normal operation when back office is back up.
	Sync Error	Synchronization error between the back office and the onboard systems	Train disengages PTC, runs at reduced speed, then resumes normal operation after error is resolved.
	Operator Error – Speed Enforcement	Train engineer does not apply brakes per onboard instructions.	Train is enforced and resumes normal operation after train engineer communicates with dispatcher.

Type	PTC Impact Event	Description	Operational Impact
	Operator Error – Other Enforcement	Other type of train engineer error that causes the onboard to enforce the train.	Train is enforced and resumes normal operation after train engineer communicates with dispatcher.

The RAM parameters – MTTR and MTBDE – of the PTCIE events were obtained from field data collected by railroads during actual PTC operation on their revenue lines. Field data was collected in two periods:

1. Data provided in 2017 from multiple Class I railroads. Most of the field data was collected from the start of PTC operation (prior to 2017) until the third quarter of 2017. Older data (prior to 2017) was used to verify trends of the RAM parameters and to help project those to the time when PTC will be fully deployed. TTCI worked with the participant railroads to identify overall improvements (in the system, people, processes) being implemented or projected to be implemented by the time PTC is fully deployed and incorporated the impact of those in the RAM parameters.
2. Data provided in 2019 from a Class I railroad. The field data contained data from 2018 operation and was used to estimate the RAM parameters for PTCIEs that the 2017 data did not contain. The railroad that provided the data was in an advanced stage of deployment, with almost the entirety of its PTC-controlled territory in revenue operation; i.e., close to full deployment. For that reason, the RAM parameters used were the values of the trends at the end of the collection period (December 2018).

Table 8 shows the list of RAM parameters and source data for each of the PTCIEs.

Table 8. List of PTC Impact Events and their RAM Parameters

PTC Impact Event	MTBDE (Hours)	MTTR (Hours)	Source
PTC wayside hardware failure[1]	14,490	1.85	2017 data
Onboard hardware non-recoverable	12,675	0.10	
Onboard software recoverable	201	0.33	
BOS-loco link[2]	21,031	2.00	
Back office downtime	4,231	0.22	
Sync error	1,668	0.45	
Operator error – speed enforcement[3]	4,965	0.10	2018 data
operator error – other enforcement[3]	596	0.10	
initialization delay[3]	4,183	0.33	
Initialization onboard hardware failure[3]	45,041	1.00	
Notes:			
[1] Same value used for all WIU types.			
[2] Not including availability of cell service.			
[3] MTTR values are based on expert opinion.			

As noted in Table 8, TTCI also included the availability of cell service as a redundant communication link between the back office and the locomotives to calculate the BOS-Loco Link. Details of the calculation of the BOS-Loco link availability is described in Appendix E.

3.1.6 Operational Disruption Events

TTCI analyzed the ability of the HRCTC methods to recover from operational disruptions. The analysis was based on typical operational disruptions (not caused by PTC) that railroads experience on a regular basis that cause a track to be taken out of service until the maintenance staff arrives at location, makes the repair, and releases it for normal operation. Long duration/catastrophic track outages were not investigated as those are considered exceptional events.

The operational disruption scenario was simulated in RTC per the following:

- Temporary speed restriction is placed at the track where the problem was reported until maintenance gang arrives:
  - 2.5-hour duration for single-track, double-track, triple-track, and non-signaled territory
  - 1.5-hour duration for DUA
- Track is taken out-of-service for repair:
  - 1.5-hour duration for single-track, double-track, triple-track, and non-signaled territory
  - 1.0-hour duration for DUA
- Track is released for normal operation.

Due to the speed restrictions and track outage, trains tend to accumulate where the event occurred. When the track is released, trains will resume operation limited to the constraints of minimum train separation and maximum speeds imposed by the train control methods. Researchers expected that more advanced forms of train control should provide better ability to recover from these types of events as they impose fewer constraints to following move operations.

RTC simulations were executed without and with operational disruptions for the same case and the train travel times from the simulations were compiled and compared to produce the results.

The method to compile and compare the results was done per the following sequence:

1. Run RTC for a scenario without disruption event and calculate total train travel time without PTC (baseline) and with another method of train control (e.g., QMB).
2. Calculate the difference between the total train travel times of the two simulation runs (e.g., baseline and QMB), as illustrated in Figure 23.
3. Run RTC for the same case but introduce the disruption event in the simulation and calculate the total train delay difference of the two simulation runs, as illustrated in Figure 24.
4. Compare the train delay results of the two scenarios with and without the operational disruption, as shown in Figure 25.

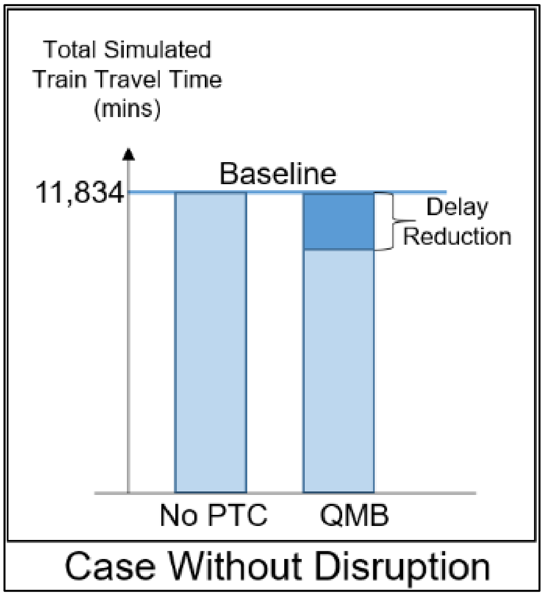


Figure 23. Calculation of Train Delay without Operational Disruption

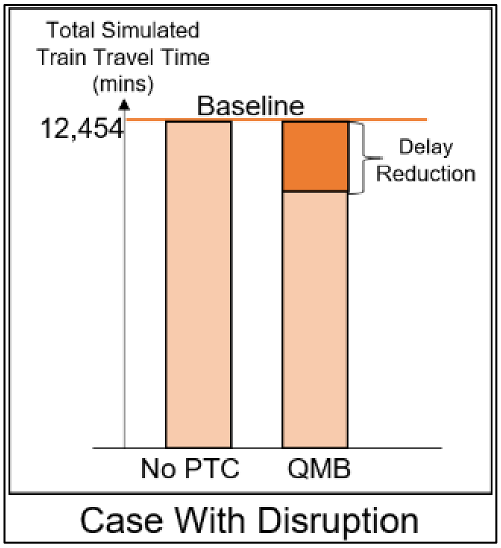


Figure 24. Calculation of Train Delay with Operational Disruption

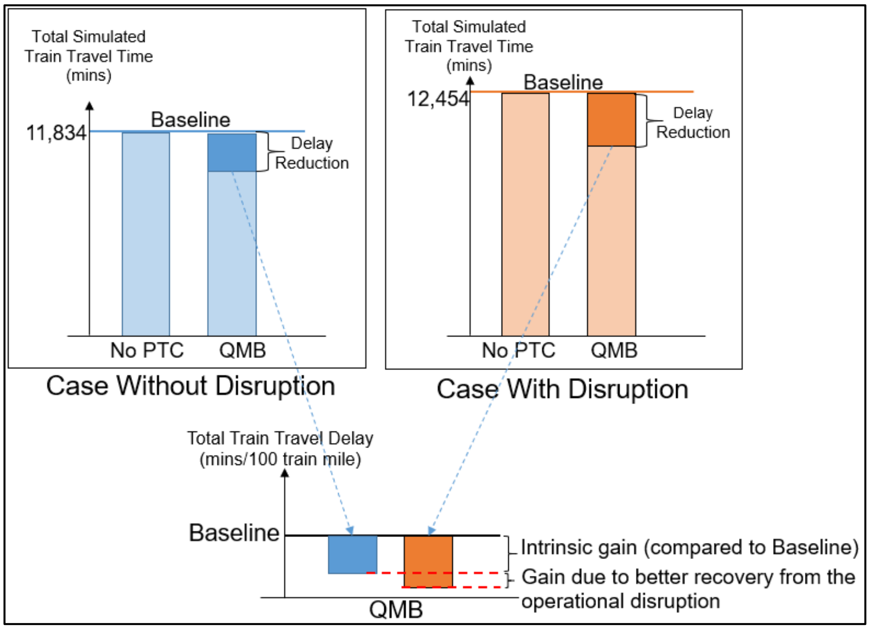


Figure 25. Comparison between the Results of the Two Disruption Scenario Cases

The difference in train delay between the two scenarios indicates the ability of an HRCTC method (such as QMB) to better recover from the operational disruption compared to the baseline. The intrinsic gain illustrated in Figure 25 indicates the capacity gain that the train control method provides compared to the baseline, independent of the operational disruption event and thus, must be distinguished when analyzing the train delay results.

3.2 Results of the Ability to Recover from Overlay PTC Analysis

TTCI analyzed the ability to recover from Overlay PTC applying the methods described in Section 3.1.

TTCI developed simulation runs for the multiple TULs (25, 50, 75, and 100 percent) as defined in Section 3.1.1., for the signaled single-track, double-track, triple-track, and non-signaled territories. For the DUA operational scenario, the simulations were run with train traffic volumes at the levels estimated for 2020, in the model based on the Chicago downtown area, as described in Appendix B. The DUA traffic volumes vary throughout the day, ranging from very high volumes in passenger routes at peak operation times (close to 100 percent TUL) to much lower volumes at non-peak-operation times. As the average daily train traffic volume in the DUA is between 50 percent and 60 percent TUL, the DUA results were included in the 50 percent TUL.

The PTC impact events were simulated only at 50 percent TUL due to limitations in the project budget; however, the train delay results without PTCIEs calculated for the other TULs can provide a good estimation of the gains that can be obtained with the proposed HRCTC methods. Table 9 shows for each TUL the operational scenarios that were analyzed are whether PTCIEs were included in the simulations.

Table 9. List of Cases Developed per TUL

TUL	**PTC Impact Event**	**Operational Scenario**				
		Single Track	**Double Track**	**Triple Track**	**Non-signaled**	**DUA**
25	NO	YES	YES	YES	YES	NO
50	YES	YES	YES	YES	YES	YES
75	NO	YES	YES	YES	YES	NO
100	NO	YES	YES	YES	YES	NO

The following subsections describe the results obtained at various TUL and with various train control methods. The total train-mile data provided by the 3 Class I railroads (Section 3.1.3) are, on average, at ~45 percent TUL, thus the overall results at 50 percent TUL provides a representative average estimation of nationwide results and was the scenario chosen to include the PTCIE simulation. Section 3.2.2 presents comparative results among train control methods per TUL. The analysis of the ability to recover from operational disruptions was conducted separately and the results are presented in Section 3.2.3.

3.2.1 Overall Results at 50 percent TUL

Figure 26 shows the results for total train delay per 100 train-miles of operation for each of the train control methods, compared with the baseline. The baseline results are for operation without PTC. The results include an aggregation of the results from all five operational scenarios (signaled single-, double-, and triple-track; non-signaled; and DUA) at 50 percent TUL. The graph to the right (a) shows the results with PTC impact events (PTC equipment failures and PTC operator errors), while the graph to the left (b) shows the results without PTC impact events. As explained in Section 2.2, the gains obtained with QMB are based on halving track circuit lengths for the signaled territories.

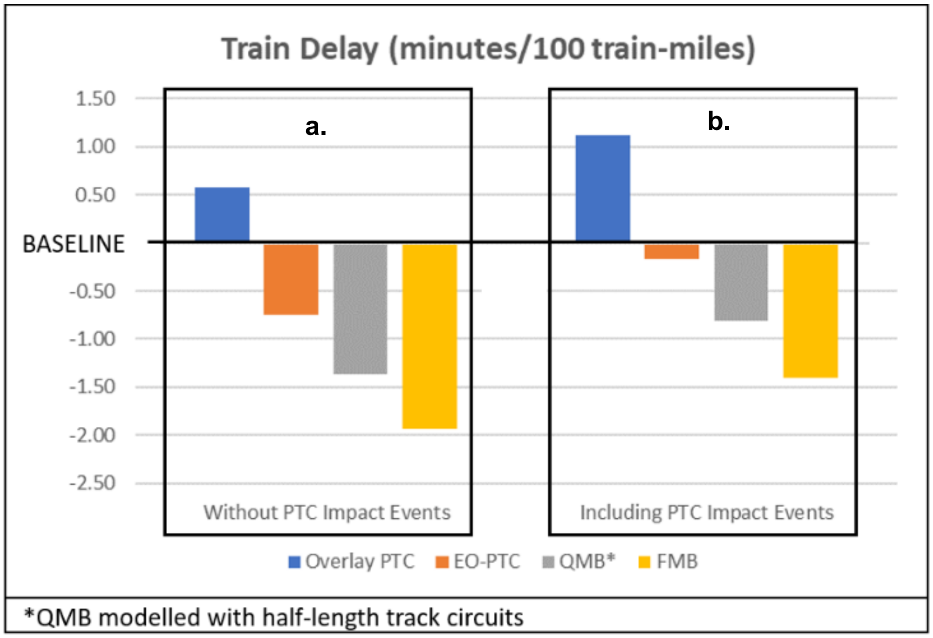


Figure 26. Total Train Delay per 100 Train-Miles at 50 percent TUL

The nationwide total train delay in hours per year was also calculated based on the nationwide numbers calculated in Section 3.1.3. Figure 27 shows the nationwide total train delay hours per year including all operational scenarios and PTCIEs based on the nationwide extrapolation numbers (see Table 5).

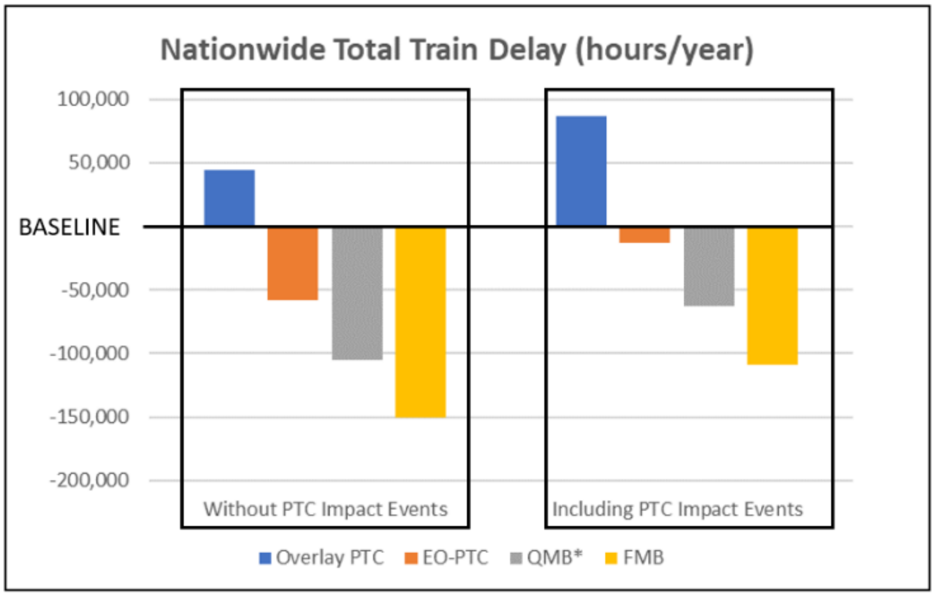


Figure 27. Total Train Delay per Year at 50 percent TUL

The train delay difference between train control methods (shown by the blue lines in Figure 28) is equivalent when comparing the cases with and without PTCIEs. Figure 28 shows that the difference between FMB and Overlay PTC remains at approximately 2.5 minutes/100 train-miles whether with or without PTCIEs. This comparison suggests that the reduction in delay when advancing the train control method remains fairly constant whether or not PTCIEs occur.

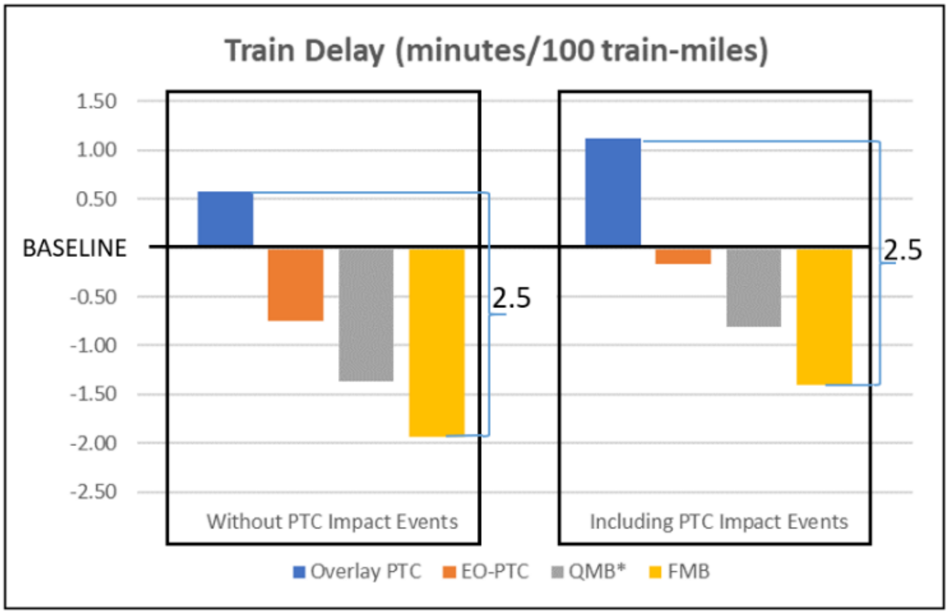


Figure 28. Comparative Train Delay Differences versus Train Control Method between Cases with and without PTCIEs at 50 percent TUL

The main takeaways from these results, given the limitations and assumptions in the analysis discussed in Section 3.1:

- EO-PTC could provide enough benefit to recover from negative impacts caused by Overlay PTC.
- Train delay decreases as train control methods advance, whether or not PTCIEs occur.

3.2.2 Comparative Results among Train Control Methods

The next set of figures show the comparative results between the train control methods per TUL and operational scenario. For all the results, the baseline is the non-PTC model and QMB is configured with half-length track circuits.

The main takeaways for the 25 percent TUL results shown in Figure 29, given the limitations and assumptions in the analysis discussed in Section 3.1:

- Greater improvements are obtained on single-track due to meet/pass resolution. Improvements are more significant when moving from Overlay PTC to EO-PTC because of relaxing the speed restrictions normally associated with Approach and Advance Approach.
- FMB gains are greater in double-track than in triple-track at this low traffic volume because, in the scenarios analyzed, double-track is predominantly freight traffic with trains operating at different speeds; triple track has a greater density of passenger and commuter traffic operating at uniform speeds. The freight trains in the double-track scenario are able to operate closer with FMB than in other methods, thus benefit more with the FMB operation compared to the passenger/commuter trains, which may already be operating closely together, given the uniformity in operation.

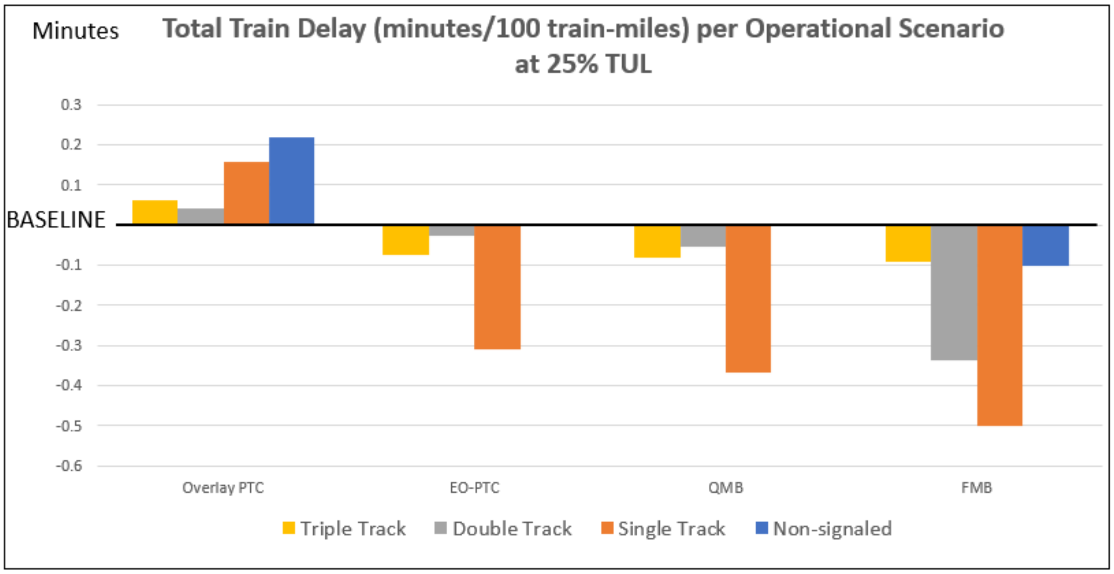


Figure 29. Total Train Delay for Each Operational Scenario at 25 percent TUL

The main takeaways for the 50 percent TUL results shown in Figure 30:

- Significant improvements are obtained in the DUA with more advanced train control methods. This may be explained by the fact that, in a DUA, a PTCIE can affect a higher number of trains. For example, if a WIU is connected to a control point that serves multiple track lines, and a train in one subdivision is delayed or stops, it affects not only traffic in the subdivision the impacted train is operating on, but it can also affect traffic from other subdivisions that converge to that subdivision.
- Train traffic volume in the DUA is near 100 percent TUL at rush hour, and there are more trains operating in close following moves that are affected by a PTCIE, which significantly influences the results.

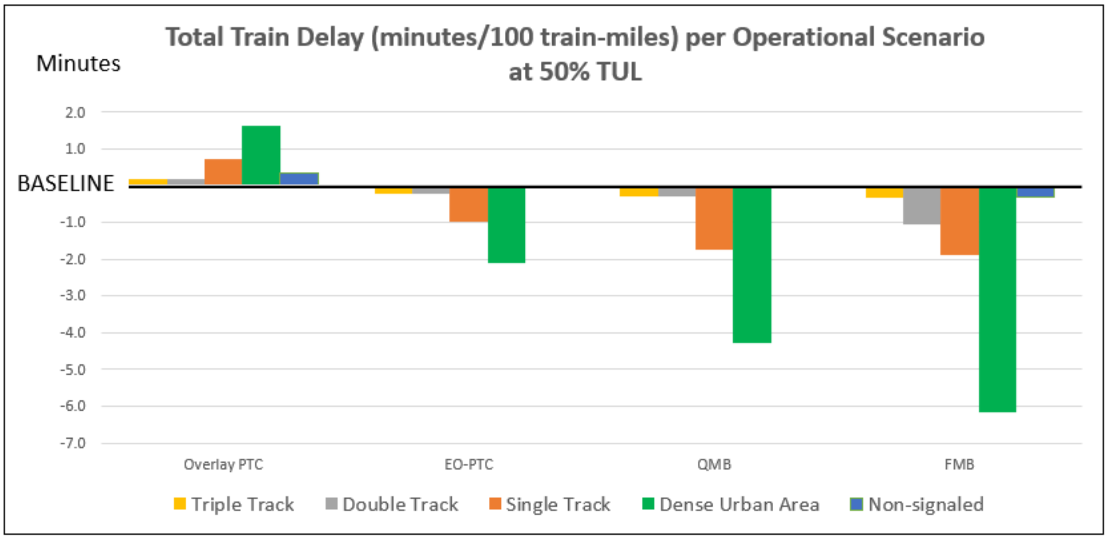


Figure 30. Total Train Delay for Each Operational Scenario at 50 percent TUL

Results in double- and triple-track scenarios at 75 percent TUL, presented in Figure 31, show greater improvement in QMB and FMB compared to lower TUL results, because with more trains operating, the ability for the trains to operate closer together in these modes of operation creates more opportunities for gains.

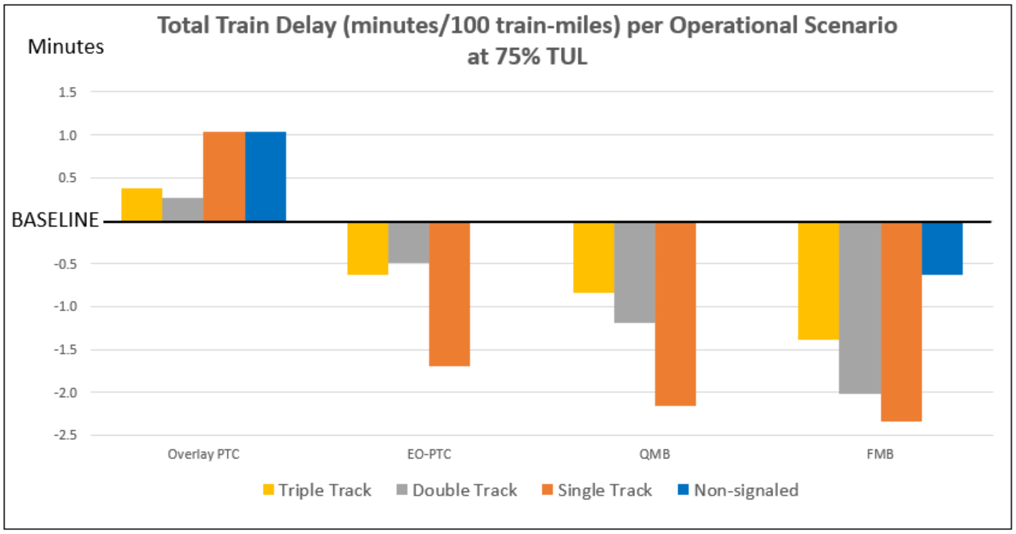


Figure 31. Total Train Delay for Each Operational Scenario at 75 percent TUL

Results in double- and triple-track scenarios at 100 percent TUL, presented in Figure 32, show increasing gains as the train control method advances similar to what was noted at 75 percent TUL. Triple-track results become more significant as compared to double-track, because the triple-track scenario modeled has predominantly passenger trains that, at higher train traffic volumes, create more opportunities for multiple impacts (i.e., impacts to a train or to a location affecting multiple trains).

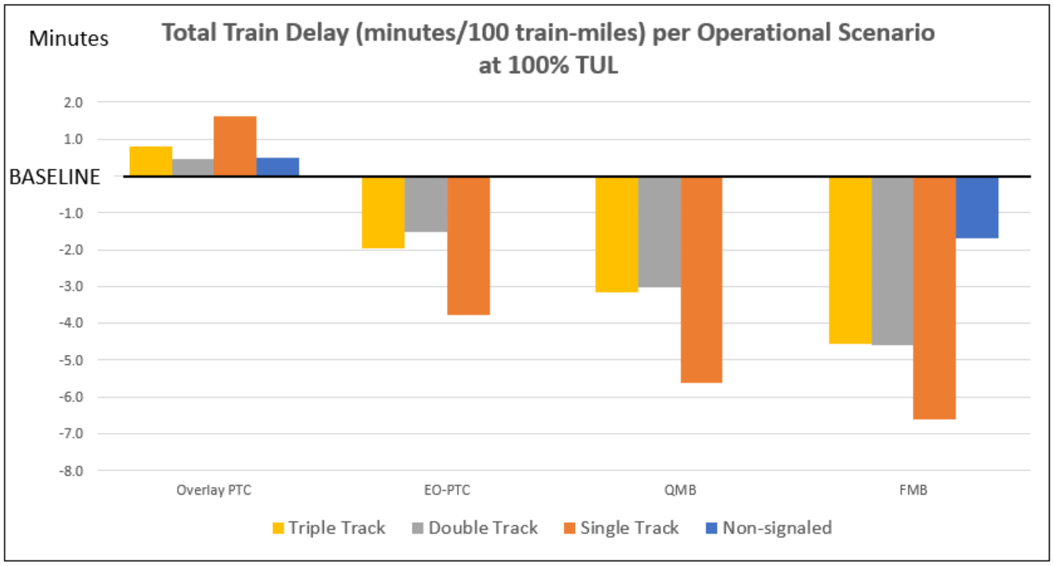


Figure 32. Total Train Delay for Each Operational Scenario at 100 percent TUL

3.2.3 Results of the Ability to Recover from Operational Disruption Events

The analysis of the ability to recover from operational disruption was developed as described in Section 3.1.6. The analysis was performed at 50 and 75 percent TUL. The results of the 25 percent TUL cases were not meaningful due to the large separation of trains, which caused few chances for train accumulation. The results of the 100 percent TUL were discarded because RTC dispatching decisions when the network becomes strangled were often masking the train delay results as a result of poor local decisions.

The results of the analysis were calculated in train delay per 100 train-miles of operation caused by the occurrence of one operational disruption event. Analysis of the DUA scenario were developed only for the projected 2020 traffic and included in the 50 percent TUL case.

Figure 33 shows the results at 50 percent TUL including all modeled operational scenarios. Figure 34 shows the results at 50 percent TUL and Figure 35 at 75 percent TUL, both without DUA results, for comparative analysis.

The main takeaways from the results:

- Ability to recover improves as the method of train control advances and density of trains increases because recovery occurs when trains accumulate – which occurs more frequently at higher train density.
- Ability to recover is greater in the DUA scenario because of the effect of trains operating over multiple tracks and the influence of passenger lines operating close to capacity at peak operation times.
- Ability to recover improves with more advanced train control methods (compared to less advanced methods) at higher TUL because: a) more advanced train control methods allow for faster recovery, and b) there is less train accumulation in more advanced methods at lower TULs.

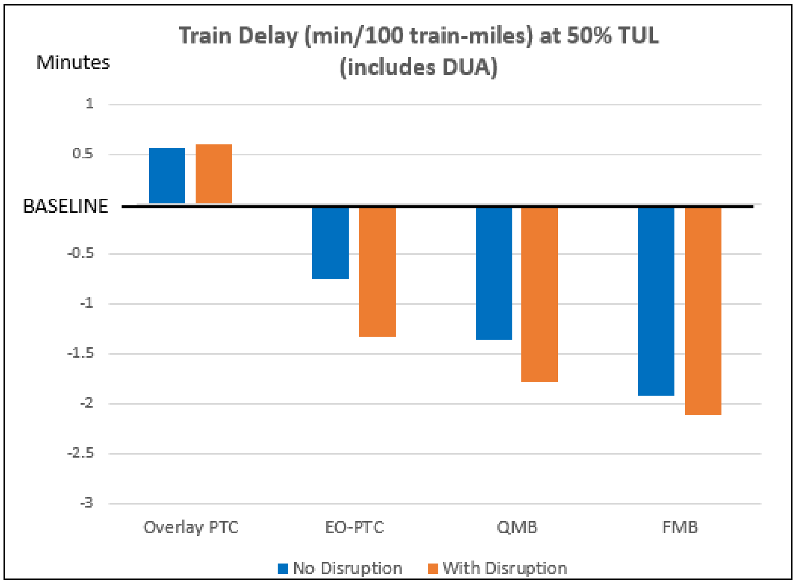


Figure 33. Capacity to Recover from Disruption Event at 50 percent TUL, Including DUA Results

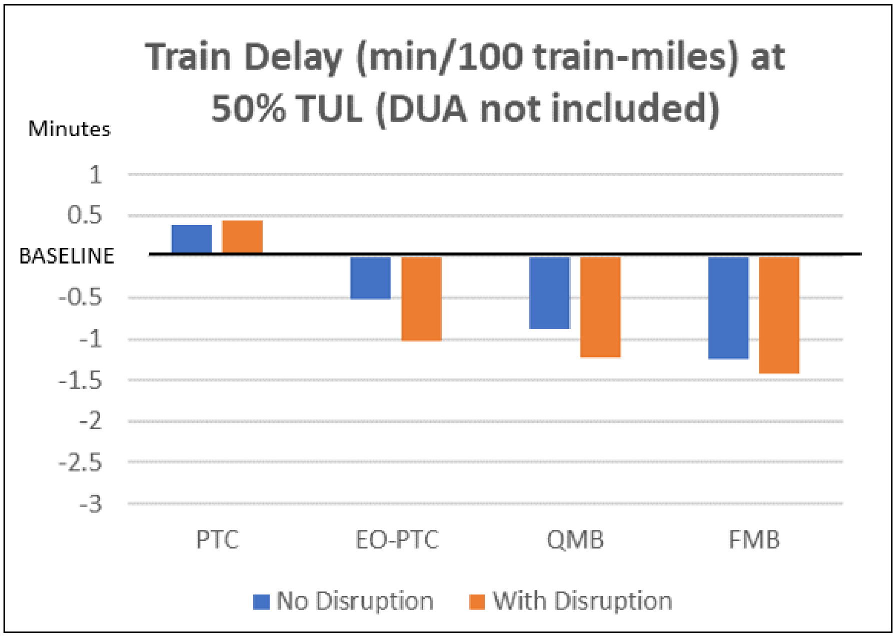


Figure 34. Capacity to Recover from Disruption Event at 50 percent TUL without DUA Results

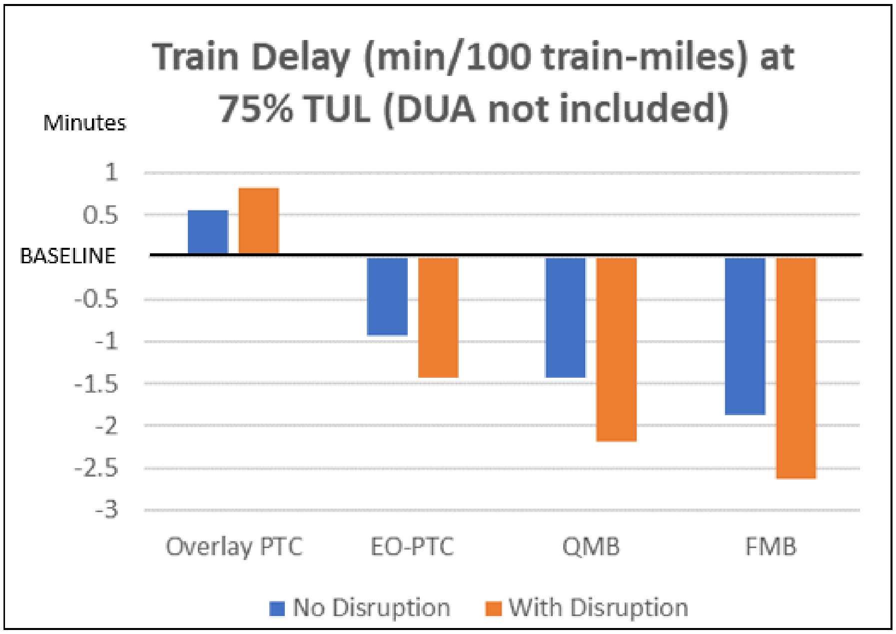


Figure 35. Capacity to Recover from Disruption Event at 75 percent TUL without DUA Results

3.2.4 RAM Analysis of PTC Impact Events

TTCI estimated the impact on train operations according to the methodology described in Section 3.1.5. The total impact on the performance of the train control methods was included in the analysis shown in Section 3.2.1. Table 10 shows the contribution of each type of PTCIE to the total train delay.

Figure 36 shows the distribution of the train delay for each type of PTCIE for the Overlay PTC method, based on the numbers shown in Table 10.

Table 10. PTCIE Train Delay (minutes/100,000 train-miles) for Each Train Control Method

PTC Impact Event	RAM Parameters (hours)		Train Delay (minutes/100,000 train-miles)			
	MTBDE	MTTR	Overlay PTC	EO-PTC	QMB	FMB
En route onboard software recoverable	201	0.33	7.7695	8.2026	7.8379	7.2673
En route operator error – other enforcement[3]	596	0.10	0.8438	0.9678	0.7929	1.0114
Initialization delay[3]	4,183	0.33	0.2167	0.2091	0.2071	0.2103
En route operator error – speed enforcement[3]	4,965	0.10	0.1013	0.1162	0.0952	0.1214
En route onboard hardware non-recoverable	12,675	0.10	0.0867	0.0943	0.0900	0.0887
En route sync error	1,668	0.45	0.0844	0.0741	0.1152	0.1387
Initialization onboard hardware failure[3]	45,041	1.00	0.0588	0.0583	0.0577	0.0586
PTC wayside hardware failure[1]	14,490	1.85	0.0208	0.0215	0.0282	0.0219
Back office downtime	4,231	0.22	0.0003	0.0002	0.0003	0.0004
BOS-loco link[2]	21,031	2.00	0.0000	0.0000	0.0001	0.0001

Notes:

[1] Same RAM values used for all WIU types.

[2] Includes availability of cell service.

[3] MTTR values are estimated.

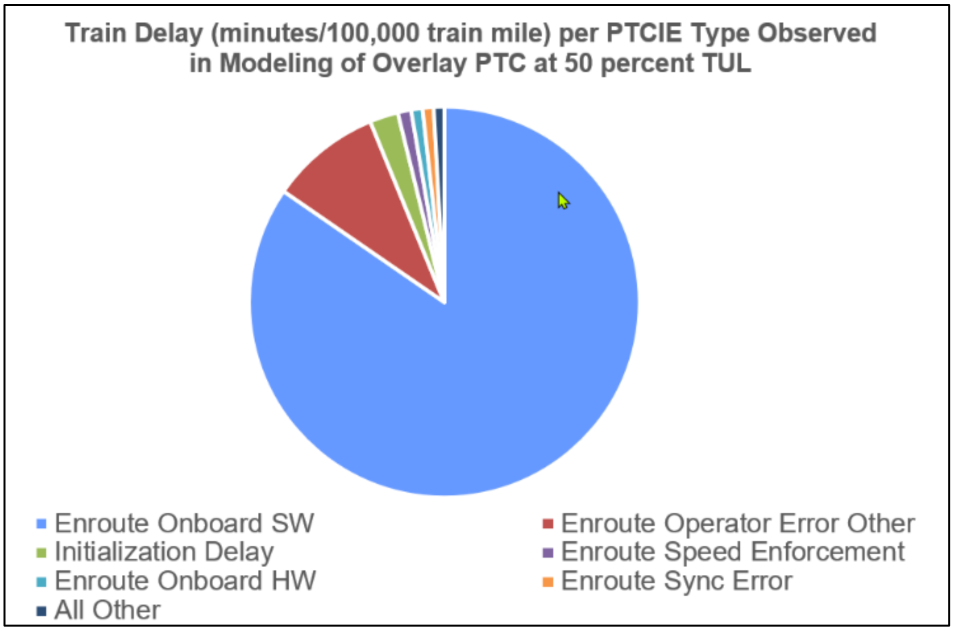


Figure 36. Relative Contribution of Each Type of PTCIE to Train Delay (minutes/100,000 train-miles) in Overlay PTC

The En Route Onboard Software Failure Recoverable type of PTCIE is the main contributor to train delay. The main reason for the high contribution of this type of PTCIE is the high number of occurrences (low MTBDE) compared to the other PTCIEs. Additionally, researchers assumed that the RAM parameters for this PTCIE would not appreciably change when PTC is fully deployed while for most of the other PTCIEs, based on 2017 data, the RAM parameters were adjusted considering trends and improvements. It is also relevant to note that the onboard segment contains software in multiple onboard segment components with interfaces to other PTC components and non-PTC systems and the actual root-cause of the event was not available for investigation in this analysis.

The next main contributor to delay is the En route Operator Error Other type of PTCIE. This may indicate that, at the time data was collected, system operators were not yet totally familiarized with the operation (i.e., still in the learning curve stage), or the system may still require adjustments to become more user-friendly.

Appendix F contains detailed results of the contribution of the PTCIEs per operational scenario and train control method.

3.3 Analysis of Capacity Increase Gains

The analysis of the capacity gains provided by the HRCTC methods was performed in two ways:

1. Estimation of theoretical maximum capacity gains developed with analytical calculations of minimum headway separation for simplified selected models.
2. Estimation developed with the results of the RTC simulations of the operational scenarios described in Section 3.1.

The subsequent subsections describe the results obtained in each case.

3.3.1 *Estimation of Theoretical Maximum Capacity Gains*

The estimation of theoretical maximum capacity was implemented with analytical formulas in Microsoft Excel for selected operational scenarios per the following:

- Various train consists: three loaded, three empty
- Two train speeds per train type: 30 mph and track speed (50, 60 and 70 mph) per train class
- Three signal block lengths: 3,000; 6,000; and 12,000 feet
- Scenario specifics:
  - Trains are uniform in type within each case modeled.
  - All trains on level single-track at constant speed in a single direction, resulting in uniform minimum headway for each scenario.
  - Performance estimates do not account for conservatism in braking algorithm and occasional loss of messages.

Figure 37 shows the results of the calculation for one scenario containing the headway separation of a train with 100 empty coal cars at 60 mph for a conventional signaling system at various block sizes, EO-PTC, and FMB. Appendix C provides detailed results of the calculations for each scenario.

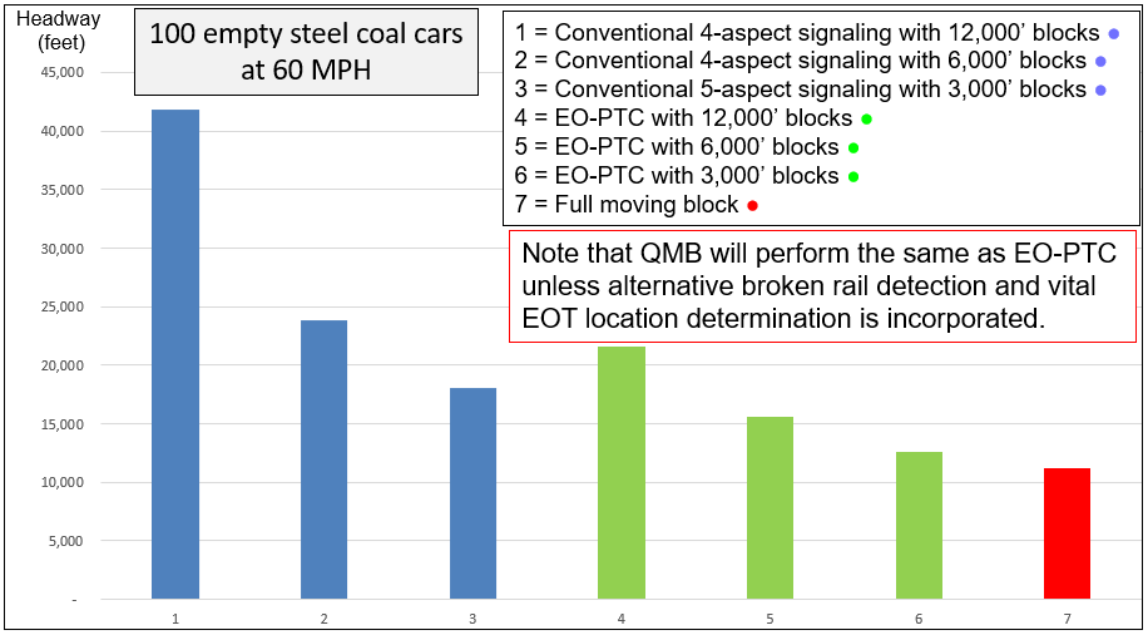


Figure 37. Theoretical Train Headway Results for Trains with 100 Empty Cars at 60 mph

The results of the analytical calculations for each case were compiled. Figure 38 shows the headway reduction percentages obtained with EO-PTC and FMB compared with conventional signaling systems.

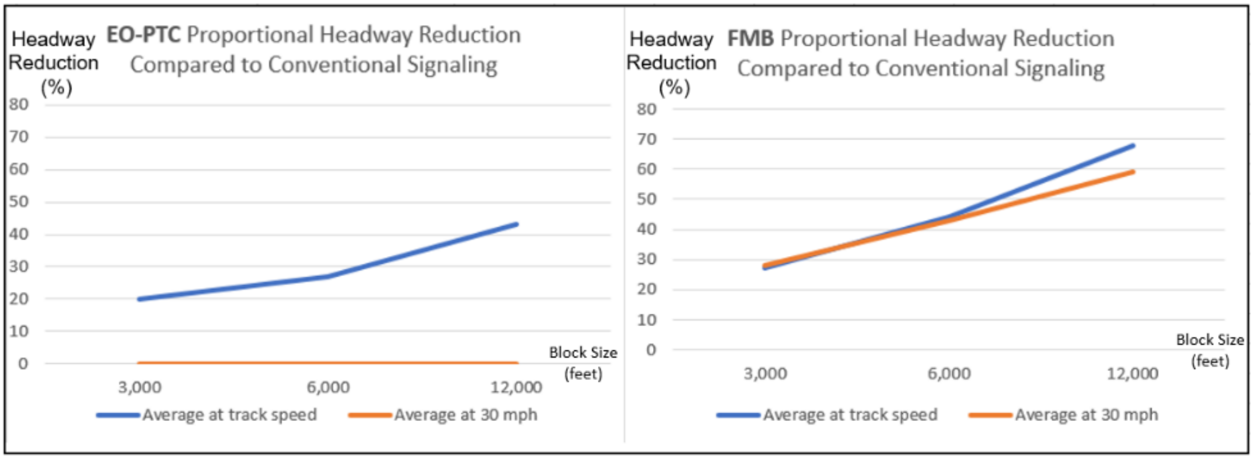


Figure 38. Compiled Results of Theoretical Maximum Headway Reduction for EO-PTC and FMB Compared to Conventional Signaling for Various Block Sizes

Based on the headway reductions, TTCI calculated the maximum theoretical capacity increases. Figure 39 shows the maximum theoretical capacity increases obtained with EO-PTC and FMB compared to conventional signaling systems.

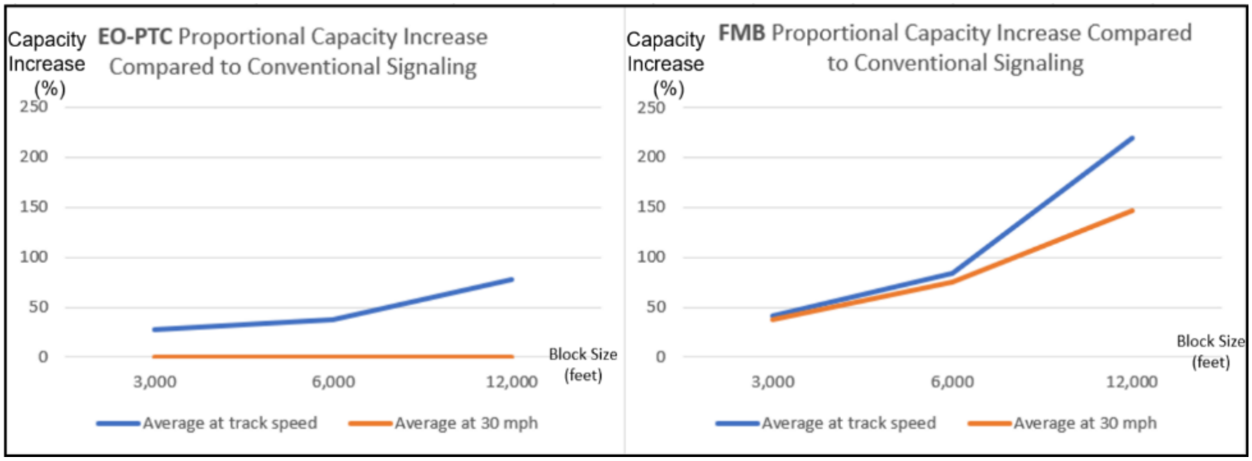


Figure 39. Compiled Results of the Theoretical Maximum Capacity Increase for EO-PTC and FMB Compared to Conventional Signaling for Various Block Sizes

The results show that, compared with conventional signaling, potential improvements from EO-PTC and FMB are significant when operating at speeds above the 30-mph restriction associated with a conventional Advance Approach signal aspect (when operating at constant speed in following moves). FMB also provides significant improvement at slower speeds.

3.3.2 Capacity Increase Based on Simulation of Operational Scenarios

While the theoretical results obtained in Section 3.3.1 show significant capacity for increase, depending on train speeds and signaling system block sizes, not necessarily all the potential capacity can be realized in actual railroad operation. To better assess what can be actually achieved under less uniform conditions, TTCI analyzed the results of the RTC simulations of the operational scenarios described in Section 3.1, as those operational scenarios are based on actual railroad configurations and operational characteristics.

The analysis is based on the comparison among the train control methods of the total train-miles operated over a certain period. The sooner a certain number of train-miles is reached under the same TUL, the more efficient the method. The analysis included only signaled single-, double-, and triple-track operational scenarios and did not include operational disruption events.

Figure 40 shows the results of the comparative performance of all train control methods considered on this project for the single-, double-, and triple-track operational scenarios, without PTCIEs nor operational disruption events. The vertical dashed lines indicate the average train trip times (minutes/100 train-miles) for each train control method at the four TULs (25, 50, 75 and 100 percent). The difference of the TUL reached at a certain train trip time, indicates the capacity increase between control methods for the particular operating point (130 minutes/100 train-miles) shown.

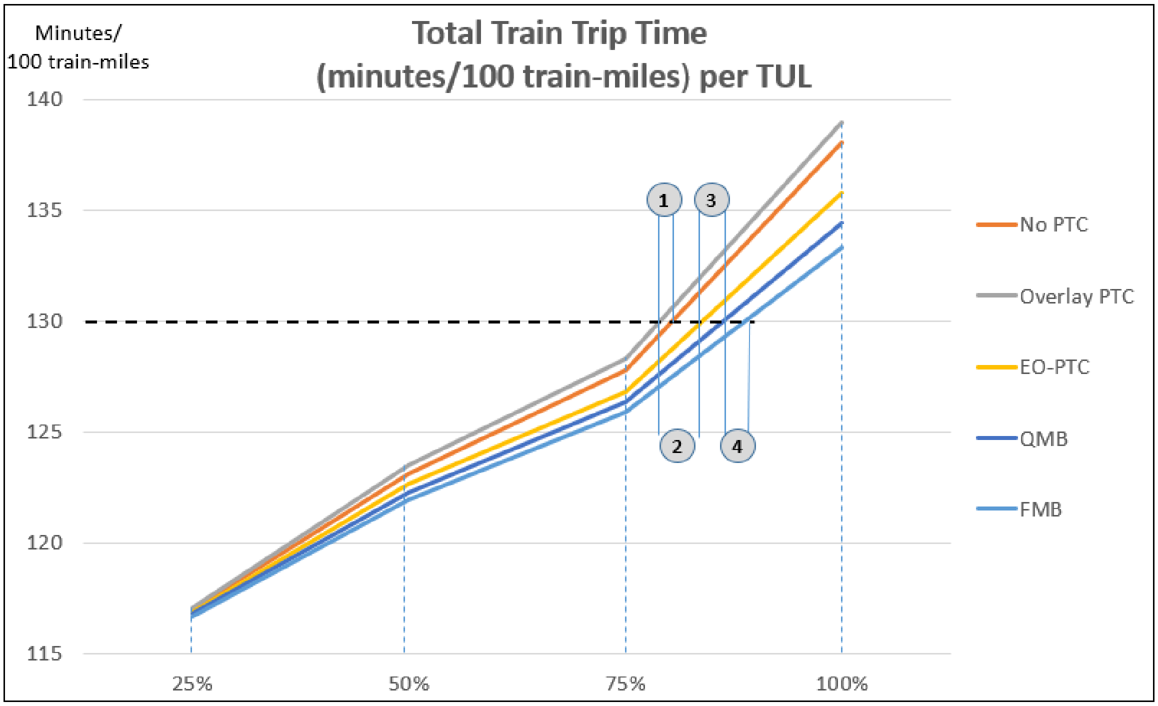


Figure 40. Capacity Increase Estimation Based on Simulation Results

The TUL values reached for each train control method at 130 minutes/100 train-miles indicated visually in Figure 40 are shown in Table 11.

Table 11. TUL at 130 Mins/100 Train-Miles per Train Control Methods

	No-PTC	Overlay PTC	EO-PTC	QMB	FMB
TUL (%)	80.5	79.0	83.9	86.4	88.9

Table 12 shows the proportional TUL differences among the train control methods. The row heading “Label” in Table 12 refers to the labels shown in Figure 40.

Table 12. Capacity Comparisons between Train Control Methods at 130 Mins/100 Train-Miles

	Train Control Method		Overlay PTC	EO-PTC	QMB	FMB
Capacity Increase (%)	Compared to Previous TC	Label	1	2	3	4
			-1.9%	6.2%	3.0%	2.9%
	Compared to no PTC		-1.9%	4.2%	7.3%	10.4%
	Compared to Overlay PTC		N/A	6.2%	9.4%	12.5%

The results shown in Table 12 are the estimated capacity gains at the selected train trip time (130 minutes/100 train-miles). More significant capacity gains are expected to occur at higher TULs based on the visual indication of Figure 40 that shows higher TUL difference between train control methods as train trip time increases.

3.4 Conclusion of the Performance Analysis Results

The results obtained from the performance analyses described in Section 3.3 are as follows:

- The proposed HRCTC methods can compensate for the negative impacts introduced by Overlay PTC.
    - Researchers expected that EO-PTC, if implemented in all PTC-controlled territories, could be sufficient to compensate for the negative impacts introduced by Overlay PTC.
    - EO-PTC performance is more significant in single-track territories, due to meet-pass encounters.
    - Territories where passenger trains are predominant provide higher performance gains at higher TUL.
    - More advanced train control methods provide greater performance gains (in terms of headway, capacity and delay) and greater ability to recover from operational disruption events.
- Theoretical maximum capacity gains show significant results, depending on train speeds and signaling system block sizes, which can reach up to more than 50 percent with EO-PTC compared to non-PTC and more than 200 percent with FMB compared to non-PTC.
- Capacity gains based on the simulation of operational scenarios increase as the train control method advances. Estimated gains when operating at approximately 80 percent practical capacity can reach:
    - A 1.9 percent reduction from non-PTC to Overlay PTC
    - A 6.2 percent increase from Overlay PTC to EO-PTC
    - A 3.0 percent increase from EO-PTC to QMB
    - A 2.9 percent increase from QMB to FMB

4. High-Level Migration Plan

The timeline and order of steps in the migration plan will determine when various developments are needed. Conversely, the projected availability of enabling technologies will influence the migration plan.

The necessity of achieving positive ROI at each incremental step will also drive the migration roadmap. This includes multiple aspects:

- Cost of implementation of the new technologies.
- Maintenance cost increases associated with the introduction of new technologies and reductions associated with the decommissioning of systems that are being replaced or no longer needed.
- Revenues associated with current and projected train traffic volumes, along with revenue impacts associated with any other resulting changes to operations.
- Costs to expand capacity with current train control methods and track (when possible as an alternative) compared with the proposed HRCTC methods.

The capacity gains obtainable with the proposed HRCTC methods will be a key factor in the decision to migrate a certain territory, particularly in areas where operation is close to practical capacity and there is demand for an increase. Depending on the traffic demand and other considerations, it is possible that a railroad may decide, for example, upon a lower-cost method that can provide the capacity gains required for a certain territory rather than adding another track. Consideration should be given to which solutions are best suited for particular scenarios or types of control territory. For example, implementing FMB train control in dark territory could be a better option than installing signaling as a means to increase capacity. FMB could also be a more cost-effective option than subdividing track circuits and increasing the number of aspects to increase capacity in very high-traffic scenarios.

The proposed HRCTC methods are conceptually defined as different modes for the same train control system, which allows railroads to operate all methods at a given time at different locations. This will require additional care in the migration plan with regard to the following aspects:

- Seamless transition of operation between train control methods
- Revision of operational and maintenance procedures, rules and documentation
- Training of operational and maintenance staff

Railroads have historically dealt with the introduction of many new train control methods and technologies that modify their operation. However, the proposed HRCTC methods may be introduced at a much faster pace than previously experienced by the railroads and the conventional train control methods currently in operation will not necessarily cease to be operated in some locations. It is likely that railroads will have to operate and maintain all train control methods – current and proposed HRCTC – at least for a certain period of time, until old train control methods can or need to be decommissioned. Some older methods of train control may never be completely retired if they are need for failure and fallback operations, or if the operation on certain territories does not justify the costs of converting to a more advanced method of train control. Special attention should be given to the aspects related to safety, both from the system design and operational procedures perspectives.

Theoretical migration paths are possible, based on the starting point of the migration; i.e., today's method of operation (CTC, ABS, TWC, etc.) with Overlay PTC. EO-PTC is a method that benefits from relaxation of the speed restrictions imposed by Approach and Advance Approach signal indications and consequently can only be implemented in signaled territories – non-signaled territories generally should not migrate to EO-PTC but most likely directly to FMB. Territories that currently have signaling can migrate to any HRCTC method. Train traffic density is another major parameter that can influence the migration plan. Higher train traffic density may justify the transition to a more advanced method of train control.

Based on the performance analysis results, shown in Sections 3.2 and 3.3, and on the design of the proposed HRCTC methods, the following factors should be considered during the migration decision analysis:

- Transition of signaled territories to EO-PTC – from the system perspective, EO-PTC only requires the editing of a track database. All other changes required for EO-PTC are related to operations (rule changes, indication, and special instructions at transition points and training). Based on that and on the expected capacity gains, even at lower train density, migration to EO-PTC is strongly recommended for all signaled territories as long as train consist information is provided with high integrity and timeliness to the PTC system.
- EO-PTC provides more significant benefits in single-track configurations. This suggests that if a railroad decides to do phased implementation of EO-PTC, single-track territories should probably be implemented sooner.
- Territories currently having high TULs (~75 percent or greater), especially those predominantly driven by passenger train traffic, are estimated to realize greater capacity gains with more advanced methods (such as QMB and FMB). Capacity gains associated with QMB and FMB implementation in such territories with lower TULs may be postponed depending on the overall ROI analysis.
- In non-signaled territories, the performance results when migrating to FMB are estimated to be considerably higher with higher train density. As shown in Section 3.2.2, total train gain at 75 percent TUL is estimated to be six times higher compared to 25 percent TUL, and 18 times higher at 100 percent TUL.

From a theoretical perspective, the individual analysis of the characteristics of each territory (be it a subdivision or portions of subdivisions) may lead to intermediate implementation steps with several transition points from one method to another at territory boundaries. While this may be the result of an optimal ROI analysis per territory, it may introduce complexity to the railroad operation and maintenance. This aspect should be considered in the overall decision analysis, which may lead to either promote or hold the advancement of the train control method for a territory even if the ROI analysis of that territory could indicate otherwise.

A particularly attractive evolution path from today's Overlay PTC implementation would be:

1. **EO-PTC:** Since this step can provide significant reduction in headways and corresponding increase in capacity without requiring any changes to the current PTC system hardware or software (only requiring changes to track data), it should provide significant near-term ROI.
2. **QMB with restricted CFM:** This mode is referred to as "restricted" because it still requires operation under RSR when a train enters an occupied block. While this mode does not provide any reduction in headways or increase in capacity as compared with EO-PTC, it is a necessary step along the evolution to FMB. And, it provides a degree of rear-of-train/restricted speed collision protection without PTL-EOT and a higher degree of protection once PTL-EOT is integrated with the QMB system. Subsequent steps would be to shorten track circuits or introduce NGTC. Alternatively, if a suitable alternative to track circuits becomes available, the ROI may be greater to proceed directly to FMB.
3. **FMB:** FMB can be implemented as a straightforward addition to QMB with restricted CFM and PTL-EOT. The key additional component needed to achieve FMB headways and capacity is an alternative method for broken rail and rollout detection.

Figure 41 illustrates the proposed evolutionary PTC steps.

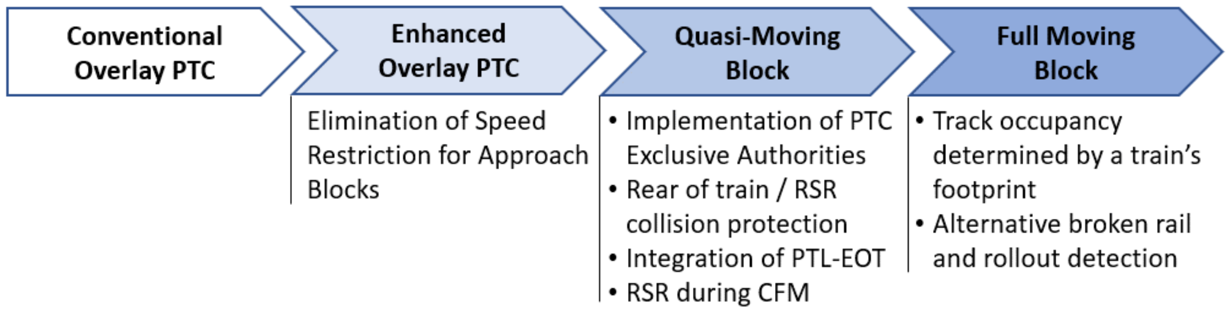


Figure 41. A Practical Roadmap through HRCTC Modes Leading to FMB

The following subsections present high-level steps for the migration to each of the proposed HRCTC methods.

4.1 Generic High-Level Migration Steps

The migration to any of the HRCTC methods will require steps that are similar for all. Additionally, there are specific steps required for each of the train control methods.

The proposed implementation and migration to a new HRCTC method involves three stages with several steps in each stage:

- Stage 1 includes lab testing.
- Stage 2 includes development and testing in a test territory.
- Stage 3 consists of the rollout and cutover of the new HRCTC method to full revenue service throughout the test territory and then in other territories after a suitable period of successful operation in the test territory.

As the train control system implementation of EO-PTC only requires editing of the track database, Stage 1 is not applicable for migration to EO-PTC.

Stage 3 includes steps for collecting before-and-after performance statistics to assess the operational benefits of the new HRCTC method as compared with the current method (either Overlay PTC or another HRCTC method) if the implementing railroad chooses to do so. This may involve operating test trains in addition to the normal revenue trains in order to determine the capacity limits of the Test Territory before and after. Optionally, a railroad might choose to collect such statistics in Stage 2 as well.

4.1.1 Stage 1 – Laboratory Testing of the New HRCTC Method

For QMB and FMB, laboratory tests and simulations of the new PTC components and functions introduced are strongly recommended. Laboratory tests will verify the correct implementation of system requirements. Simulations can help check the proper configuration of the system for a particular territory before cutting it over to revenue service. A simulation environment with an actual test bed (with actual tracks, trains, and system components) may be extremely helpful to accelerate the validation of the system requirements. Proposed steps for this stage:

1. Develop a test plan and procedures for use in lab tests. The test plan and procedures must address all system requirements, including functional and non-functional requirements. Simulation of virtual components (such as trains, tracks and other) can be used to verify validate requirements and configuration parameters, including those that require multiple train operation and complex scenarios. The procedures will identify all train operations (simulated moves) to take place during the test as well as all types of data to be collected. Efficiency can be increased by designing tests to allow verification of multiple requirements per test run.

   The project manager or project engineer will prepare the test plan along with support from personnel such as those who have responsibility for safety, signaling/train control implementation, communications implementation, operations, and executing/monitoring tests as well as supplier(s). It may be helpful to develop a Requirements Verification Conditions and Criteria Matrix (RVCCM) prior to developing the Test Procedures.
2. Prepare laboratory environment for the execution of the test plan. Actual PTC equipment (e.g., TMCs, WIUs, test server, test CAD) and equipment to simulate locomotive interfaces, track circuit interfaces, and other relevant features of the railroad operating environment should be included within the laboratory test system. Multiple configurations may be required for the execution of unit and integration test scenarios. Integration tests can be executed in groups of sub-systems per turn.
3. Conduct the tests per the test plan. Sequence of tests typically start with the execution of unit tests, culminating with entire system integration tests. Tests typically start with the execution of functional tests.
4. Upon completion of the functional tests, review the results and address issues found with the project team. Vendors may have to be involved with the resolution of problems found. If necessary, redo the tests and address remaining issues until problems found are resolved.

5. Once functional tests are completed without errors, non-functional tests will be executed. These include response time and system capacity among others. Simulators likely will be required for system capacity testing.
6. Upon completion of the non-functional tests, project team will review the results and address issues. Vendors may be involved with the resolution of problems found. If necessary, redo the tests and address remaining issues until problems found are resolved.
7. Review results of the tests with railroad's engineering staff and operation management and decide whether to proceed with Stage 2 or take other actions.

4.1.2 Stage 2 – Preparation for and Field Testing of the New HRCTC Method

Before a railroad begins transitioning territories to the new HRCTC method in full revenue service, a one-time test sequence should be performed with a special test train in a designated test territory (HRCTC Test Territory or test bed) to verify that the modifications to PTC implementation, configuration, rules, and training have been properly executed. Proposed steps for this testing:

1. Develop a test plan and procedures for use in the HRCTC Test Territory. The procedures will identify all train operations (moves) to take place during the test as well as all types of data to be collected. The test plan and procedures must address trains operating in, as well as trains transitioning into and out of, the HRCTC Test Territory. The test cases must also include simulated failure and fallback situations. The Test Plan from Stage 1 should be used as a starting point, if that stage was executed.
   The project manager or project engineer will prepare the test plan along with support from personnel such as those who have responsibility for safety, signaling/train control implementation, communications implementation, operations, and executing/monitoring tests as well as supplier(s). It may be helpful to develop a RVCCM prior to developing the Test Procedures, that can be leveraged from Stage 1, if done at that stage.
2. Develop crew and dispatcher instructions for trains operating in, as well as trains transitioning into and out of, the HRCTC Test Territory. The instructions must also include procedures to handle failure and fallback situations including how to safely handle any incidents that might occur. These instructions will eventually become part of a general order and ultimately the railroad's rulebook and timetable/special instructions. Emphasize the critical importance of keeping the Information System (IS) data correct, dispatcher and crews always maintaining accurate current consist data in the PTC system.
   Personnel for that railroad's department responsible for the handling of operational rules likely will draft these instructions. This draft document will be reviewed by the HRCTC project manager and other railroad personnel such as those who have responsibility for safety, signaling/train control implementation, operations, and executing/monitoring tests.
3. Based on input from the railroad operation management and the HRCTC project manager, select a section of track and a set of locomotives and cars (and service units, if applicable) to be used as the test train(s) in the HRCTC Test Territory along with a time period for testing. This will be reviewed and approved by railroad management. The Test Territory should be suitable for loading with extra train traffic to determine capacity limits of the territory.
4. Develop processes and tools to support modifications to the PTC system.

5. For the transitions to and from the HRCTC territory, special accommodation may be required. These may require installation of signs in the field and modifications to existing systems.

   Railroad signaling department personnel will likely execute this task as directed by the HRCTC project manager. Capital costs will be associated with any changes to equipment configuration.

6. Train and certify crews and dispatchers for conducting test operations in the HRCTC Test Territory. Training personnel will develop training materials and certifications. Materials will be reviewed by the HRCTC project manager as well as safety and operations personnel. Training personnel will conduct the training and certification.

   A PTC onboard simulator may be used to support training if appropriately configured. When modifications to the simulator are required, the supplier of the simulator would likely be involved.

7. Prepare for testing of the HRCTC:
   a. Coordinate with the railroad operations management and define appropriate date/time to perform the field test.
   b. Railroad management will inform operating and test/engineering personnel of when testing will take place.
   c. Implement required field, locomotive, and back office system modifications. This also includes developing equipment and software for monitoring the train control system and logging test data.

8. When approaching the scheduled date/time for the test, the HRCTC project manager confirms the availability of the track and test assets with railroad operations and organizes the resources for the execution of the tests.

9. Issue a Track Bulletin for the test territory with instructions for revenue trains about how to avoid interference with or to coordinate movements with the test train(s). Conduct a safety briefing and then commence testing per the HRCTC Test Plan and Test procedures. This would involve the HRCTC project manager, train crews, a dispatcher, and test personnel (that may include supplier personnel) in the field and at the back office for the duration of the testing. Certain personnel and equipment will be designated for logging test results and any anomalies or safety concerns.

10. Upon completion of tests, coordinate with the railroad operation to restore prior system operations in Test Territory (unless railroad wishes to keep HRCTC in revenue service operation there). Inform operating personnel that testing is complete and restore non-test track database and configuration files as well as software versions in locomotives that were involved in testing. This would involve the same test personnel as Step 7. Cancel the Track Bulletin that was issued for testing.

11. Assess results of testing and decide whether to proceed to revenue service roll-out of HRCTC or modify plans and testing. Address issues found during the tests with the project team. Vendors may have to be involved with the resolution of problems found. If necessary, redo the tests and address remaining issues until problems found are resolved.

This would be performed by the HRCTC project manager with support from the railroad's engineering staff and operation management.

4.1.3 Stage 3 – Cutover of the new HRCTC Method into Revenue Service

Many of the steps for cutover of the new HRCTC method into Revenue Service territory leverage analogous steps discussed above for Stage 2.

Proposed steps for cutting over the new HRCTC method into revenue service:

1. If the implementing railroad wishes to quantify the new HRCTC benefits, develop a data collection plan to obtain baseline operations data prior to the new HRCTC cutover. Extra trains may need to be operated to determine the capacity limits of the territory. The HRCTC project manager with support from engineering and/or data analytics staff will define the data to be collected.
   The suggested data to be collected are train throughput, headways in close following moves (not just average, but collect and store data on train locations frequently throughout the test), transit times experienced by all trains on the territory over a sufficient period of time (from which can be determined average velocity, delays.), and anomalies (warnings, enforcements, etc.). The data collected needs to include meta data, such as time of day, day of week, time of year since the benefits of the new HRCTC (to be collected after cutover) are primarily experienced during peak traffic times. Any events that can impact traffic (e.g., slow orders, work zones, extra trains) must also be recorded along with their start and end times, locations, type of disruption. In order to attain statistically significant data for the appropriate situations, some fake slow orders or work zones may need to be introduced. Additionally, data on the amount of time for each train to recover (resume full speed) from each event that slows or stops trains, and data on the amount of time taken to reach full speed after exiting a yard, terminal, or slow order would be beneficial.
2. Develop an HRCTC test plan and procedures for use in revenue service in the new HRCTC territory, as well as transitions into and out of the territory. The documents will be prepared by the HRCTC project manager or project engineer along with personnel such as those who have responsibility for safety, signaling/train control implementation, communications implementation, operations, executing/monitoring tests, and supplier(s). Development of these documents can significantly leverage off of those developed in Stage 2.
   a. The test plan will be used by the first train (likely a test train) with test personnel onboard. The train will be operated once in each direction over the entire territory before it is cut over to revenue service (instead of having to go through Stage 2 for every territory). This is done to verify that the territory has been configured properly, that all WIUs are communicating the proper new information, and that the track database is correct for the new train control method.
   b. A track bulletin will be issued for the time that the test train is making its run, after which revenue trains will operate normally (not following a test plan/procedure). They will, however, have been instructed on what sort of issues to watch for and will be required to fill out a PTC post-trip report noting any anomalies after every trip through the territory for a designated number of months.

3. Issue a general order (and ultimately an update to the railroad's timetable/special instructions and rulebook) with the crew and dispatcher instructions for trains operating in, as well as trains transitioning into and out of, the new HRCTC territory. The instructions must also address failure and fallback situations. Emphasize the critical importance of keeping the IS data correct, and the importance of the dispatcher and crews always maintaining accurate and current consist data in the PTC system.

   Development of these documents would leverage those developed in Stage 2.

4. Based on input from the railroad operation management, select the territories to be converted to the new HRCTC territory along with the sequence in which they will be converted. Validate the selection and sequence of territories with the railroad operation management.
5. Implement the changes required in the field and in the existing systems. Railroad signaling department personnel will likely execute this task as directed by the HRCTC project manager.
6. Train and certify crews and dispatchers for operating in the new HRCTC territory. A PTC onboard simulator appropriately configured may be used. Training personnel will develop training material and certification procedures. Materials would be reviewed by the HRCTC project manager. Development of these documents would leverage those developed in Stage 2. Training personnel will conduct the training and certification.
7. Prepare for cutover of HRCTC:
   a. Coordinate with the railroad operations management and define appropriate date/time to start the cutover.
   b. Railroad management will inform operations, test, and engineering personnel of when cutover will take place in each territory, based on a recommendation from the HRCTC project manager.
   c. If required, install signs along the wayside indicating where HRCTC begins and ends. If field signals are in operation, and the new HRCTC system does not require them for operation (i.e., QMB and FMB), be prepared to bag the signals when the cutover to the new system starts. These tasks will be conducted by maintenance-of-way (MoW) personnel.
      i. It is possible (optional) that field signals would remain in place, unbagged, when a territory is first cut over to QMB. This would facilitate more efficient handling of trains that have not been upgraded to QMB (e.g., those belonging to a tenant) or that have failed PTC onboard equipment.
      ii. If a railroad chooses to keep signals operating unbagged for a while after cutting over the QMB, then there will be extra steps associated with the subsequent transition to elimination of signals, since crews will have to follow different rules in QMB territory with signals present versus. without signals present.
   d. Issue General Order indicating exactly when and where the new HRCTC method will be cut over.
8. Cutover the new HRCTC method.

   a. Per the sequence of territories agreed with the operation, start the new HRCTC cutover. Adjust the exact date/time of the cutover for each territory with the railroad operation management and inform all personnel involved with the cutover.
   b. Issue Track Bulletin (e.g., Form C) instructing crews operating on the newly cut over HRCTC territory to watch for and report any anomalies experienced to the dispatcher immediately and on their PTC Trip Report, which should be completed after every trip through the territory until anomalies become rare.
   c. If necessary, update system versions and databases for each HRCTC territory at the time of that territory's cutover.
   d. If required, uncover signs at the new HRCTC territory boundaries. If field signals are in operation, and the railroad has decided to operate without them, bag the field signals. MoW personnel will conduct these tasks.
   e. Monitor the operation of trains under the territories that were cut over. If problems related to the operation of the new HRCTC method are reported, discuss them with the railroad operation management to decide whether to proceed with the new HRCTC operation, repair the problem, or to restore operation with prior train control method. Address issues found by the project team. Vendors may have to be involved with the resolution of problems found. If necessary, redo the tests and address remaining issues until problems found are resolved. If field signals need to be restored to operation, those should be unbagged by the MoW personnel.
9. After cutover of each territory, if applicable, collect statistics on operations on the territories according to the data collection plan previously developed in Step 2.
10. Compare the results with those collected for the same territory prior to cutover to determine the amount of improvement provided by the new HRCTC method.

4.2 EO-PTC High-Level Specific Migration Steps

The implementation of EO-PTC does not require the introduction or removal of new PTC system components. From the perspective of the PTC system, it only requires modification to a system track database. Additionally, the railroads will have to train operators, make modifications to operating rules, and install physical signs in the field at territory boundaries, if necessary.

For Stage 1 steps (Preparation for and Field Testing), the following need to be considered:

- In Step 4, include modifications to the track database file for EO-PTC purposes (it is likely possible to build upon the existing track database file modification processes).
- In Step 5, develop and verify a modified track database for the EO-PTC Test Territory that maps signals as required for EO-PTC.
- In Step 8, upload the modified track database onto test locomotives just prior to testing.

For Stage 2 steps (cutover of the new HRCTC Method into Revenue Service), the specific steps are also related to the track database in a similar fashion as the modifications in Stage 2. In Steps 5 and 8, make specific changes in the PTC system related to updates in the track database. All other Stage 3 high-level steps remain as per the generic steps.

4.3 QMB High-Level Specific Migration Steps

QMB introduces new PTC system components and new operational concepts as compared to Overlay PTC and EO-PTC. This will require the execution of Stage 1 before Stage 2. The generic stages should be adjusted to include, per segment:

- Back office: New set of functions to handle the concept of exclusive enforceable authorities for all trains. Optionally, the railroad may also decide to implement Centralized Interlocking, which also requires a new set of functions in the back office.
- Onboard: Modification of existing functions to handle the concept of exclusive, enforceable authorities for all trains at all times in PTC territory. Optionally, the railroad may also decide to implement PTL-EOT.
- Wayside: Modifications to the WIUs to report status of track circuits (simply “Clear” or “Not Clear”) as opposed to signal indication; decommissioning of field signal aspects. Optionally, the railroad may also decide to implement CIXL, which will require modifications to wayside systems (interlocking and interfaces with back office system).
- Communications: Additional message traffic to accommodate exclusive, enforceable authority and PTL-EOT message traffic. Depending on how CIXL is implemented, additional message traffic may have to be handled by the communication system for that as well.

Modifications to Stage 2 and Stage 3 (Sections 4.1.1 and 4.1.3) migration steps include specific procedures to implement and test each of the PTC components being introduced. The migration will follow the same steps as stated in the generic migration stages; however, detailed testing and implementation plans specific to QMB will have to be developed. Particular attention must be paid to testing the unrestricted close following move (CFM) functionality (with PTL-EOT and NGTC, if that solution is chosen) since train crews will have to rely upon the PTC system for knowing how to operate the train during CFM because wayside signals will not convey information in this regard.

For QMB to provide greater capacity/shorter headways than EO-PTC, changes to the track circuits will be required, such as shortening them or implementing NGTC. These changes to the track circuits will require testing across the entire territory where deployed.

In Stage 2, step 4 (processes and tools to support modifications to the PTC system) may include the ability to simulate a phantom train moving along a track at the same time that an actual train is following. This would test the ability of the system to warn of and enforce the appropriate safe minimum headway between them at various speeds, consists, etc., especially for the case of unrestricted CFM. A non-revenue test bed may be useful for this test.

If CIXL is being implemented, a detailed plan to switch over the field interlocking must be prepared, which may require manual field intervention to switch back and forth and likely phased migration (sets of continuous interlocking locations). Special attention should be given to transition areas where CIXL will have to interface with legacy field interlocking systems.

4.4 FMB High-Level Specific Migration Steps

Similar to QMB, FMB will introduce new PTC system components and new operational concepts as compared to Overlay PTC and EO-PTC. This will require the execution of Stage 1 before Stage 2. The migration plan to FMB depends on the type of train control method that it is migrating from:

- QMB: FMB will require the introduction of an alternate broken rail detection method. This system will require testing at various speeds and for various types of track and breaks. PTL-EOT and CIXL are also required for FMB if the QMB implementation from which it is migrating has not yet implemented them.
- Non-signaled territory: Will require all the new PTC components introduced with QMB plus an alternate broken rail detection method if anticipated increased train density and/or speeds necessitate the addition of broken rail protection. In this scenario, there is no need to migrate from an existing signaling system, which simplifies the migration process.

As in QMB, in Stage 2, step 4 (processes and tools to support modifications to the PTC system) may include the ability to simulate a phantom train moving along a track at the same time that an actual train is following it. This would test the ability of the system to warn of and enforce the appropriate safe minimum headway between them at various speeds, consists, etc. A non-revenue test bed may be useful for this test, as well as testing of the alternative broken rail and rollout detection system.

5. High-Level Feasibility Analysis

QMB and FMB methods require the introduction of new technologies currently at various implementation/maturity levels. They also introduce new requirements on existing PTC components that need to be verified from a feasibility perspective.

EO-PTC does not introduce new system components or requirements and therefore does not raise any questions from the feasibility perspective.

The technologies and sets of requirements that are being introduced with QMB and FMB and thus require a feasibility analysis are described in the following sections.

5.1 Positive Train Location – End-of-Train

The development of a PTL system has been an ongoing effort from the railroad industry. FRA has sponsored research projects in this area since 2010. The main objective of the PTL system is in improving the accuracy and dependability of determining the location of trains.

Most PTC systems rely on GPS-based, head-of-train (HOT) location determination systems, which generally are not sufficient on their own for safety critical track discrimination or determination of train length for train control purposes. The original goal of PTL was to be able to determine the position of the front of the train and the rear of the train to an accuracy of less than 1.2 meters, at a confidence level of 99.999999997 percent (10 nines), to determine train length and track discrimination. While this accuracy has been attainable at the HOT, this performance could not at that time be affordably achieved at the EOT. Initial testing faced technical challenges that included:

- High bit error rate (BER) in the communications link between front of train and rear of train at required ranges associated with 900 MHz operation
    - EOT antenna directionality and squinting: The back of the rearmost railcar directly obscured line-of-sight (LOS) communication between EOT segment and HOT segment resulting in significant LOS signal attenuation.
    - Antenna positioning and multipath fading: Signal multipath resulted in destructive interference for a single HOT antenna configuration. As a result, link reliability was significantly reduced.
- Limited bandwidth with 220 MHz and 450 MHz data radio operation
- Rearmost car constellation masking: The back of the rearmost railcar often obscured up to half the available Global Navigation Satellite System (GNSS) constellation and diminished satellite geometric dilution of precision (GDOP).
- GNSS antenna positioning and orientation: The back of the rearmost railcar further acted as a multipath reflector that biased position estimates.

FRA is currently sponsoring TTCI to continue with the research efforts to address the challenges above for the implementation of PTL-EOT. The most recent research has yielded updated requirements and a revised conceptual solution including new technology that is expected to overcome the challenges experienced in the earlier efforts.

TTCI has also been investigating the application requirements and message traffic demands for PTL-EOT under the QMB Phase 1 project, funded by FRA. Initial assessment indicates that the additional message traffic required for PTL-EOT can likely be supported with the existing 220-MHz spectrum owned by PTC220 LLC, even at high density train traffic territories. However, some higher than predicted loading is being experienced at certain locations with the current Overlay PTC system that, if not reduced, may indicate a need for additional radio link capacity to support QMB in high density areas.

5.2 Alternate Broken Rail Detection

Track circuits have been in use for more than a century and are the primary means of detecting track occupancies for driving automatic block signals (ABS) in North America. The same track circuits are also used to detect rail breaks.

Track circuits are not 100 percent effective at detecting rail breaks, however. Due to their fixed boundary locations and their typical lengths in signal system deployments, conventional track circuits are not generally suitable for use with FMB train control systems. This is because a primary objective of most FMB systems is to allow near minimum theoretical headways between trains when operating at speeds up to track speed. Shorter headways can result in greater traffic capacity.

With fixed block systems, there must be at least one unoccupied block (plus train braking distance) between two trains operating in a following move to operate safely at speeds above restricted speed. The unoccupied block is excess train spacing above what is theoretically required. Further, since block signaling systems use fixed locations of track circuit boundaries and signals, these locations must be based on braking distance of the worst braking train that can operate over that territory at track speed. This results in additional excess train spacing because the average train requires less braking distance. FMB train control systems do not inherently impose these forms of excess train spacing, but consequently require a less restrictive form of rail break detection.

While it is possible to reduce the amount of excess train spacing by reducing block length (and increasing the number of signal aspects if conventional signaling is retained), this increases the number of track circuits required, which can be prohibitively expensive. Several alternatives to conventional track circuits have been conceived for detecting rail breaks in support of FMB train control. These alternatives are categorized below:

- Advanced track circuits (“next generation track circuits” or NGTC)
- Non-track circuit-based wayside broken rail detection systems
- Onboard broken rail detection systems (OBRD)

No practical/affordable alternative wayside broken rail detection system for use with FMB train control is currently in production. Tests of various conceptual and prototype solutions falling in the categories listed have taken place over the past few decades or are currently underway.

A few advanced track circuit solutions are being prototyped and show strong potential to detect a rail break within a block that has one occupancy. Once a second train enters the block, however, no broken rail detection can take place between the two trains. This accommodates a partial reduction in headways as compared with what is achievable under conventional fixed-block signaling, which makes this solution attractive for use with QMB. The advanced track circuit solutions do not, however, support the maximum capacity benefit otherwise achievable with FMB train control.

Non-track-circuit-based, wayside broken rail detection systems include those that detect and locate vibration/sound or strain along the rail. Fiber optic acoustic detection (FOAD) systems can detect and locate a break while a train is passing over it, but FOAD has not yet been implemented in a fail-safe manner for vital train control applications. Systems that transmit and receive sound through the rail are in use on a few railroads but are costly, due to the large number of transceivers that must be installed along track. Similarly, strain gage systems require a large number of devices to be installed along track.

A few onboard broken rail detection systems have strong potential to support FMB. An onboard system is attractive in that it might be more affordable to equip trains rather than track locations, since there are far fewer trains in operation than there are track circuit equipment sites on a railroad. Further, rail vehicles can usually be maintained at a facility rather than sending maintenance personnel to the field. Some onboard systems can detect a rail break underneath a train or just after a train clears a break. A broken rail detection system mounted on a DP locomotive at the end of a train might be feasible in the relatively near term. Existing track circuits would likely be retained for detecting spontaneous breaks (those rare breaks that do not occur under a train). It would be more desirable, however, if an onboard system could detect a rail break that is beyond the braking distance of a train ahead, which can be on the order of a couple of miles. This could allow elimination of track circuits altogether. To date, no onboard system is available with that range, but attempts are underway by TTCI to achieve that goal.

Following is a summary of the feasibility for alternative broken rail detection for each of the various modes of HRCTC:

- EO-PTC – No alternative broken rail detection system is required. EO-PTC operates with conventional track circuits.
- QMB – Can be implemented without alternative broken rail detection, but advanced track circuits are required. to achieve the full potential capacity improvements that QMB can offer. A couple of advanced track circuit solutions look promising and might be available for installation within the relatively near future.
- FMB – At least two different OBRD systems that can be used at the rear of a train to support FMB are available from suppliers. They have undergone a limited amount of testing and revenue service operation to date. Regarding solutions other than OBRD at the end of a train, a significant amount of development and testing remains to be done before any that can support FMB become viable (reliable, fail-safe, producible, and affordable).

5.3 Centralized Interlocking

Centralized interlocking is not a new concept – railroad vendors, particularly in Europe, have already developed and deployed commercial products that implement the core concepts of centralized interlocking that will be required for QMB and FMB. However, many of the existing systems only implement conventional interlocking functions; QMB and FMB require the integration of exclusive enforceable authorities with interlocking functionality.

Technical challenges may exist in the implementation of functions and interfaces with QMB and FMB components, but those are not expected to be significant. The main challenge that requires careful design resides in the requirements for message communication among the back office, field devices, and trains controlled by a centralized interlocking such as switches and track circuits. The implementation of the centralized interlocking functions should not be a pure replication of conventional field interlocking designs which could create not only extreme requirements for the communication system such as very low latency and high message traffic volume, but also unnecessary complexity in the centralized interlocking functions. Peer-to-peer communications of real-time wayside status to trains is key to addressing the challenge.

5.4 Movement Authority Functionalities

The implementation of the exclusive enforceable authority functions, both in the onboard and back office components, may also have technical challenges. Fail-safe design and verification is required for some of the movement authority functions to guarantee that train authorities are exclusive (i.e., not overlapping), depending on the chosen architecture. Fail-safe designs for train control systems have been extensively used by the railroad industry and should be achievable in this case.

The main technical challenge to implement the exclusive enforceable authority functionalities relates to the capacity of the PTC communication system to support the additional message traffic required for the operation of QMB and FMB. In both train control methods, trains will be periodically releasing portions of track behind them as they move to allow for the extension of authorities for following trains. This process introduces additional message traffic for the PTC communication system.

TTCI has developed an initial assessment of the additional QMB message traffic under the FRA-funded QMB Phase 1 project. Initial assessment indicates that the additional message traffic required for QMB might be supported with the existing 220-MHz PTC radios and the spectrum owned by PTC220 LLC, even at high density train message traffic territories. But some concerns are yet to be addressed before a solid conclusion can be drawn about the sufficiency of the existing PTC communications capacity.

For FMB, additional message traffic capacity may be required either to allow trains to operate at closer proximity and/or for the implementation of alternate broken rail detection technology that will work in conjunction with the movement authority functions. Preliminary assessment of additional message traffic in QMB indicates that this is not expected to be significant enough to become a technical challenge and FMB should not be much different than QMB. This, however, is yet to be verified.

6. Conclusion

The three HRCTC methods identified in the evolution of PTC – EO-PTC, QMB, and FMB – are estimated to not only compensate for the negative impacts of Overlay PTC, but to increase railroad capacity when compared to non-PTC operations. EO-PTC, if deployed in all signaled PTC-controlled territories, is estimated to provide capacity gains in the range of approximately 4 percent at high train density (~80 percent TUL) while FMB gains are estimated in the range of approximately 10 percent, based on the operating scenarios analyzed.

The results of the simulations and analysis indicate that the HRCTC methods can provide greater gains compared to non-PTC or Overlay PTC operation as the density of trains increases. The HRCTC methods are also estimated to have better capacity to recover from operational disruption scenarios when compared to non-PTC or Overlay PTC operation.

Based on the RAM analysis of the PTCIEs, issues related to onboard software are the largest contributors to impact upon railroad efficiency. The second largest contributor is Operator Errors that cause enforcement (note that Operator Errors in this context does not include failure to comply with the PTC braking curve).

The HRCTC methods are at different levels of readiness for deployment. EO-PTC can be implemented without software or hardware changes requiring only changes to the configuration of the track database, modification of rules, and modification of training. QMB requires modification or development of new PTC software components, as well as new technologies in its full configuration (with optional PTL-EOT, optional NGTC, and optional CIXL). Most of these technologies are not fully developed for PTC. FMB will substantially leverage from QMB and will require an alternative broken rail detection system. QMB and FMB will require additional message traffic over the radio system, but preliminary assessment indicates that existing PTC220 LLC spectrum and radio throughput might be sufficient.

As the results are based on average numbers, assumptions, and the field data collected at the time, the analysis was prepared. Further investigation and analysis can be done to better determine which of the proposed train control methods to deploy and when, or to determine improvements in RAM parameters of PTC components that are worth implementing including:

- Analysis of operational and safety impact and potential gains for specific actual scenarios and/or specific configuration of a railroad territory
- Use of latest field data collected by railroads to determine input parameters for RAM analysis with greater accuracy.
- Improvements in PTC features of railroad network simulation tools to better represent the actual system, future designs and new technologies being added to PTC.

The tools and methods prepared for this project can be used to promote further analysis that better supports decisions related to the deployment of the proposed methods, including the development of the above listed items.

Based on the concepts defined during the development of this project, multiple spin-off projects were initiated for EO-PTC, QMB, FMB, and associated technologies. As of the fourth quarter of 2019, four spin-off projects from the HRCTC program had already been awarded by FRA and other projects had been selected by railroad committees with high priority for development.

7. References

[1] Federal Railroad Administration. PTC Implementation Status by Railroad. https://www.fra.dot.gov/app/ptc/

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[4] Pate, S. (2018). Research on Methods for Enhancing Positive Train Control Freight Braking Algorithms. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

[5] Vieira, P. (2018). Northeast Corridor PTC Radio Frequency Network Design. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

[6] Brosseau, J. (2013). Development of an Operationally Efficient PTC Braking Enforcement Algorithm for Freight Trains. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration.

Appendix A: Configuration of Operational Scenario Simulation Models

The RTC simulation models of the selected operational scenarios were designed to characterize typical train operations in different types of tracks to assess potential impacts in capacity and/or safety associated with the operation under PTC. The models were also used to quantify potential improvements that the proposed train control methods can provide and verify if it can offset the negative effects of current Overlay PTC.

The configuration of the scenarios were defined jointly with the AG, based on operational characteristics provided by participant railroads. Table 13 shows a summary of the primary configuration parameters per operational scenario.

Table 13. Primary Operational Scenario Configuration Parameters

Operational scenario	Track length (miles)	Number of WIUs	Number of sidings or crossovers
Signaled single-track	204	99	20
Signaled double-track	204	162	27
Signaled triple-track	109	108	25
Non-signaled territory	204	99	20
Dense urban area	108	108	21

However, the scenarios needed additional information to be fully configured; specifically:

- Length of sidings in the single-track and dark territory scenarios
- Spacing between sidings in single-track and dark territory scenarios
- Spacing between crossovers in the double- and triple-track scenarios
- Track circuit length in the single-, double-, and triple-track, as well as dense urban area scenarios
- Track altimetry in all the scenarios
- Track curvature in all the scenarios
- Switch characteristics
- Train consist makeup and schedule for all the trains in all the scenarios

Configuration details for each operational scenario such as siding length, typical track circuit length in signaled territories, etc. were based on typical subdivisions selected by participant railroads and approved by the AG, per the following:

- Signaled single-track: Red Rock subdivision (BNSF)
- Signaled double-track: Mendota subdivision (BNSF)
- Signaled triple-track: Kearney subdivision (UP)
- Non-signaled territory: Red Rock subdivision (BNSF), used as reference for the geometry.

- DUA: Multiple subdivisions from several railroads (including Metra, Amtrak, BNSF, Belt Railway Company of Chicago (BRC), Canadian National Railway (CN), Norfolk Southern Railway (NS), and Union Pacific Railroad (UP) in the Chicago DUA. The RTC model prepared for FRA's PTC Radio Frequency Network Design for Dense Urban Areas study [2] were used as reference to create the DUA model for this project.

Signaled Single-Track Scenario Configuration

Using BNSF's Red Rock subdivision as the baseline to model the geometric characteristics of this scenario, TTCI analyzed the following sections of this subdivision:

- From milepost 411.3 to 517 (at this point, there is a change in milepost enumeration to 417)
- From milepost 417 to 387.4 (skipped from milepost 387.4 to 380.6 as this is a double-track configuration)
- From milepost 380.6 to 312

Grades and curves were configured to characterize significant variations. Track circuit sizes were configured with average size, based on the sizes identified in the tracks analyzed. Table 14 shows the details of the configuration for the signaled single-track model.

Table 14. Signaled Single-Track Configuration Parameters

Length (miles)	204
Number of sidings	21
Length of sidings (min., max., avg. miles)	1.1, 2.1, 1.738
Spacing between sidings (min., max., avg. miles)	4.4, 11.5, 7.614
Sidings type	Controlled
Track circuit length (min., max., avg. miles)	1.85, 2.55, 2.147
Number of permissive signals	58
Number of absolute signals	42
Elevation (min., max. feet)	720, 1210
Degree of curvature (min., max. degrees)	0, 6.05
Switch type	Dual-controlled
Frog number of the switches	20
Type of train control	CTC
Maximum speed (passenger, freight mph)	79, 60

The configuration of the trains included in the model was based on information provided by the participant railroads and reviewed with the AG. The number and type of trains for the signaled single-track scenario were in total 17 daily trains, with the following distribution: 4 passenger, 3 loaded grains, 2 empty grains, 2 high-priority merchandise, 2 UPS freight, 2 merchandise, 1 unit (other than coal or grain), and 1 intermodal stack. Sixty-five percent of the trains depart from one end of the track, and 35 percent from the other end.

The train consist was based on typical parameters obtained from an analysis of the configuration of trains that currently run in actual subdivisions. Table 15 shows the train schedule and consist configuration of the signaled single-track model.

Table 15. Signaled Single-Track Train Schedule

Train ID	Type	Departure Time	Entry Point	# of Cars	Locomotive Type	No. of Loco-motives	Total Weight (tons)	Total Length (feet)	P/W Ratio
Amtrak-01	Passenger	7:30 AM	East	8	F59PH	2	300	676	20.2
Amtrak-02	Passenger	7:40 AM	West	8	P40-HEP	2	608	818	8.4
LoadedGrain-01	Loaded Grain	8:55 AM	East	100	SD40-2	3	11000	5706	0.7
Merchandise-01	Merchandise	9:05 AM	West	90	C44-9	2	7650	5996	1.1
EmptyGrain-01	Empty Grain	10:20 AM	East	100	SD40-2	3	3500	5706	2.2
LoadedGrain-02	Loaded Grain	10:30 AM	West	100	SD40-2	3	11000	5706	0.7
UPS-01	Freight	11:45 AM	East	50	SD70MAC	2	4400	3298	1.5
HPM-01	High-Priority Merchandise	11:55 AM	West	70	SD70MAC	2	5110	4558	1.3
Amtrak-03	Passenger	1:00 PM	West	8	P40-HEP	2	608	818	8.4
Merchandise-02	Merchandise	1:10 PM	East	80	SD70MAC	2	6800	5348	1
Amtrak-04	Passenger	2:20 PM	East	8	F59PH	2	300	676	20.2
IS-01	Intermodal Stack	2:25 PM	West	70	SD70MAC	3	6300	5122	1.6
EmptyGrain-02	Empty Grain	3:50 PM	West	100	SD40-2	3	3500	5706	2.2
Unit-01	Unit (other than coal or grain)	5:20 PM	West	110	SD70MAC	2	10450	6748	0.6
LoadedGrain-03	Loaded Grain	6:40 PM	West	100	SD40-2	3	11000	5706	0.7
HPM-02	High-Priority Merchandise	8:05 PM	West	70	SD70MAC	2	5110	4558	1.3
UPS-02	Freight	9:30 PM	West	50	SD70MAC	2	4400	3298	1.5

Signaled Double-Track Scenario Configuration

Using BNSF's Mendota subdivision as the baseline to model the geometric characteristics of this scenario, TTCI analyzed 125 miles of this subdivision (from MP 165 to 40).

TTCI prepared a 204-mile-long model using the track configuration identified in the Mendota subdivision.

TTCI applied the same track altitude and curvature configuration defined for the single-track scenario. All track circuits between two control points were assumed to have the same length.

Track circuit sizes were configured with average size, based on the sizes identified in the tracks analyzed. Table 16 shows the details of the configuration for the signaled double-track model.

Table 16. Signaled Double-Track Configuration Parameters

Length (miles)	204
Number of crossovers	24
Length of sidings (min., max., avg. miles)	N/A
Spacing between crossovers (min., max., avg. miles)	3.9 , 15.8 , 8.01
Crossovers type	Single and double
Track circuit length (min., max., avg. miles)	1.3 , 2.14 , 1.689
Number of permissive signals	188
Number of absolute signals	96
Elevation (min., max. feet)	728.5 , 1180
Degree of curvature (min., max. degrees)	0 , 6.05
Switch type	Dual-controlled
Frog number of the switches	20
Type of train control	C.T.C.
Maximum speed (passenger, freight mph)	79 , 60

The double-track model was configured with total 86 trains per day, with the following distribution: passenger, 39 loaded grains, 4 empty grains, 17 high priority merchandise, 2 UPS freight, and 18 merchandise. Fifty-one percent of the trains depart from one end of the track and 49 percent from the other end.

Table 17 shows the train schedule and consist configuration of the signaled double-track model.

Table 17. Signaled Double-Track Train Schedule

Train ID	Type	Departure Time	Entry Point	No. of Cars	Loco-motive Type	No. of Loco-motives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Dbl-01	Loaded Grain	12:00 AM	East	100	SD40-2	3	110,00	5,706	0.7
Dbl-02	Merchandise	12:15 AM	West	90	C44-9	2	7,650	5,996	1.1
Dbl-03	High-Priority Merchandise	12:30 AM	East	70	SD70MAC	2	5110	4,558	1.3
Dbl-04	Loaded Grain	12:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-05	Freight (High-Prt Merch)	1:15 AM	West	50	SD70MAC	2	4400	3,298	1.5
Dbl-06	Loaded Grain	1:30 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-07	Loaded Grain	1:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-08	Loaded Grain	2:00 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-09	Loaded Grain	2:15 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-10	Merchandise	2:30 AM	East	80	SD70MAC	2	6800	5,348	1
Dbl-11	Loaded Grain	2:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-12	Loaded Grain	3:00 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-13	Merchandise	3:15 AM	West	90	C44-9	2	7650	5,996	1.1
Dbl-14	Loaded Grain	3:30 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-15	Merchandise	3:45 AM	West	90	C44-9	2	7650	5,996	1.1
Dbl-16	Loaded Grain	4:00 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-17	High-Priority Merchandise	4:15 AM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-18	Merchandise	4:30 AM	East	80	SD70MAC	2	6800	5,348	1
Dbl-19	Loaded Grain	4:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-20	Merchandise	5:00 AM	East	80	SD70MAC	2	6800	5,348	1
Dbl-21	High-Priority Merchandise	5:15 AM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-22	High-Priority Merchandise	5:45 AM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-23	High-Priority Merchandise	6:00 AM	East	70	SD70MAC	2	5110	4,558	1.3
Dbl-24	Passenger	6:15 AM	West	8	P40-HEP	2	608	818	8.4
Dbl-25	High-Priority Merchandise	6:30 AM	East	70	SD70MAC	2	5110	4,558	1.3
Dbl-26	Loaded Grain	6:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-27	Loaded Grain	7:00 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-28	High-Priority Merchandise	7:15 AM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-29	Passenger	7:30 AM	East	8	F59PH	2	300	676	20.2
Dbl-30	Empty Grain	7:45 AM	West	100	SD40-2	3	3500	5,706	2.2

Train ID	**Type**	**Departure Time**	**Entry Point**	**No. of Cars**	**Loco-motive Type**	**No. of Loco-motives**	**Gross Weight (tons)**	**Total Length (ft.)**	**P/W Ratio**
Dbl-31	Loaded Grain	8:00 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-32	Loaded Grain	8:15 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-33	Loaded Grain	8:30 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-34	Loaded Grain	8:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-35	Loaded Grain	9:00 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-36	Loaded Grain	9:15 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-37	Loaded Grain	9:30 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-38	Empty Grain	9:45 AM	West	100	SD40-2	3	3500	5,706	2.2
Dbl-39	Empty Grain	10:00 AM	East	100	SD40-2	3	3500	5,706	2.2
Dbl-40	Loaded Grain	10:15 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-41	Loaded Grain	10:30 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-42	Loaded Grain	10:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-43	Loaded Grain	11:15 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-44	Loaded Grain	11:30 AM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-45	Loaded Grain	11:45 AM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-46	Loaded Grain	12:00 PM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-47	Loaded Grain	12:15 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-48	Loaded Grain	12:30 PM	East	100	SD40-2	3	11000	5,,706	0.7
Dbl-49	High Priority Merchandise	12:45 PM	West	70	SD70MAC	2	5110	4558	1.3
Dbl-50	Loaded Grain	1:00 PM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-51	Loaded Grain	1:15 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-52	High-Priority Merchandise	1:30 PM	East	70	SD70MAC	2	5110	4,558	1.3
Dbl-53	Merchandise	1:45 PM	West	90	C44-9	2	7650	5,996	1.1
Dbl-54	Loaded Grain	2:00 PM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-55	Merchandise	2:15 PM	West	90	C44-9	2	7650	5,996	1.1
Dbl-56	Loaded Grain	2:30 PM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-57	Merchandise	2:45 PM	West	90	C44-9	2	7650	5,996	1.1
Dbl-58	Loaded Grain	3:00 PM	East	100	SD40-2	3	11000	5,706	0.7
Dbl-59	Passenger	3:15 PM	West	8	P40-HEP	2	608	818	8.4
Dbl-60	Merchandise	3:30 PM	East	80	SD70MAC	2	6800	5,348	1
Dbl-61	Loaded Grain	3:45 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-62	Merchandise	4:00 PM	East	80	SD70MAC	2	6800	5,348	1
Dbl-63	Loaded Grain	4:15 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-64	Merchandise	4:30 PM	East	80	SD70MAC	2	6800	5,348	1
Dbl-65	Freight (High-Prt Merch)	5:00 PM	East	50	SD70MAC	2	4400	3,298	1.5

Train ID	Type	Departure Time	Entry Point	No. of Cars	Locomotive Type	No. of Locomotives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Dbl-66	Merchandise	5:15 PM	West	90	C44-9	2	7650	5,996	1.1
Dbl-67	High-Priority Merchandise	5:30 PM	East	70	SD70MAC	2	5110	4,,558	1.3
Dbl-68	Merchandise	5:45 PM	West	90	C44-9	2	7650	5996	1.1
Dbl-69	Merchandise	6:00 PM	East	80	SD70MAC	2	6800	5,348	1
Dbl-70	Passenger	6:15 PM	East	8	F59PH	2	300	676	20.2
Dbl-71	High-Priority Merchandise	6:15 PM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-72	Merchandise	6:45 PM	West	90	C44-9	2	7650	5,996	1.1
Dbl-73	Merchandise	7:00 PM	East	80	SD70MAC	2	6800	5,348	1
Dbl-74	Loaded Grain	7:15 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-75	Empty Grain	7:30 PM	East	100	SD40-2	3	3500	5,706	2.2
Dbl-76	Loaded Grain	7:45 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-77	High-Priority Merchandise	8:00 PM	East	70	SD70MAC	2	5110	4,558	1.3
Dbl-78	High-Priority Merchandise	8:15 PM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-79	High-Priority Merchandise	8:45 PM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-80	High-Priority Merchandise	9:00 PM	East	70	SD70MAC	2	5110	4,558	1.3
Dbl-81	Merchandise	9:15 PM	West	90	C44-9	2	7650	5,996	1.1
Dbl-82	High-Priority Merchandise	9:45 PM	West	70	SD70MAC	2	5110	4,558	1.3
Dbl-83	Merchandise	10:00 PM	East	80	SD70MAC	2	6800	5,348	1
Dbl-84	Loaded Grain	10:15 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-85	Loaded Grain	10:45 PM	West	100	SD40-2	3	11000	5,706	0.7
Dbl-86	High-Priority Merchandise	11:00 PM	East	70	SD70MAC	2	5110	4,558	1.3

Signaled Triple-Track Scenario Configuration

Using UP's Kearney subdivision as the reference to build the signaled triple-track model, TTCI analyzed 109 miles of track (from MP 284.0 to 175.0) to determine the configuration parameters for the model.

The altitude and curvature of tracks of the model were based on the same characteristics as the tracks of the signaled single-track model. The length of track circuits between two control points were configured with average track circuit length.

Table 18 shows the details of the configuration for the signaled triple-track model.

Table 18. Signaled Triple-Track Configuration Parameters

Length (miles)	109
Number of crossovers	16
Length of sidings (min., max., avg. miles)	N/A
Spacing between crossovers (min., max., avg. miles)	2.2, 10.6, 6.188
Crossovers type	Single and double
Track circuit length (min., max., avg. miles)	1.067, 1.5, 1.252
Number of permissive signals	207
Number of absolute signals	96
Elevation (min., max. feet)	953 , 1150
Degree of curvature (min., max. degrees)	0 , 4.0
Switch type	Dual-controlled
Frog number of the switches	20
Type of train control	C.T.C.
Maximum speed (passenger, freight mph)	79 , 60

The model was configured with 110 daily trains, distributed as follows: 75 passenger, 5 loaded grains, 1 empty grain, 8 loaded coal, 4 high-priority merchandise, 4 intermodal, 4 intermodal stack, 2 UPS freight, 4 merchandise, 1 empty coal, 1 vehicle, and 1 unit (other than coal or grain). From these trains, 52 percent will depart from one end of the track and 48 percent from the other end. Table 19 shows the train schedule and consist configuration of the signaled double-track model.

Table 19. Signaled Triple-Track Train Schedule

Train ID	Type	Departure Time	Entry Point	No. of Cars	Locomotive Type	No. of Loco-motives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-01	Freight	12:10 AM	East	50	SD70MAC	2	4,400	3,298	1.5
Tri-02	Intermodal	12:40 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-03	Freight	1:15 AM	West	50	SD70MAC	2	4,400	3,298	1.5
Tri-04	Intermodal	1:20 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-05	Intermodal	1:45 AM	West	70	SD70MAC	3	6,300	5,122	1.6
Tri-06	Intermodal Stack	2:20 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-07	Intermodal	2:45 AM	West	70	SD70MAC	3	6,300	5,122	1.6
Tri-08	Intermodal Stack	3:15 AM	West	70	SD70MAC	3	6,300	5,1,22	1.6
Tri-09	Intermodal Stack	3:20 AM	East	70	SD70MAC	3	6,300	5,122	1.6
Tri-11	High-Priority Merchandise	4:00 AM	East	70	SD70MAC	2	5,110	4,558	1.3
Tri-10	Intermodal Stack	4:00 AM	West	70	SD70MAC	3	6,300	5,122	1.6

Train ID	Type	Departure Time	Entry Point	No. of Cars	Locomotive Type	No. of Loco-motives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-12	Passenger	4:06 AM	West	8	P40-HEP	2	608	818	8.4
Tri-13	Passenger	4:30 AM	West	8	P40-HEP	2	608	818	8.4
Tri-14	High-Priority Merchandise	4:40 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Tri-15	Passenger	4:52 AM	West	8	P40-HEP	2	608	818	8.4
Tri-16	High-Priority Merchandise	5:00 AM	East	70	SD70MAC	2	5,110	4,558	1.3
Tri-17	Passenger	5:15 AM	West	8	P40-HEP	2	608	818	8.4
Tri-18	Passenger	5:30 AM	West	8	P40-HEP	2	608	818	8.4
Tri-20	Passenger	5:45 AM	East	8	F59PH	2	300	676	20.2
Tri-19	Passenger	5:45 AM	West	8	P40-HEP	2	608	818	8.4
Tri-21	Passenger	5:52 AM	West	8	P40-HEP	2	608	818	8.4
Tri-22	Passenger	6:12 AM	West	8	P40-HEP	2	608	818	8.4
Tri-23	Passenger	6:32 AM	West	8	P40-HEP	2	608	818	8.4
Tri-24	Passenger	6:45 AM	East	8	F59PH	2	300	676	20.2
Tri-25	Passenger	6:52 AM	West	8	P40-HEP	2	608	818	8.4
Tri-26	Passenger	7:00 AM	East	8	F59PH	2	300	676	20.2
Tri-27	Passenger	7:12 AM	West	8	P40-HEP	2	608	818	8.4
Tri-28	Passenger	7:20 AM	East	8	F59PH	2	300	676	20.2
Tri-29	Passenger	7:25 AM	West	8	P40-HEP	2	608	818	8.4
Tri-31	Passenger	7:45 AM	East	8	F59PH	2	300	676	20.2
Tri-30	Passenger	7:45 AM	West	8	P40-HEP	2	608	818	8.4
Tri-33	Passenger	8:00 AM	East	8	F59PH	2	300	676	20.2
Tri-32	Passenger	8:00 AM	West	8	P40-HEP	2	608	818	8.4
Tri-34	Passenger	8:15 AM	West	8	P40-HEP	2	608	818	8.4
Tri-36	Passenger	8:30 AM	East	8	F59PH	2	300	676	20.2
Tri-35	Passenger	8:30 AM	West	8	P40-HEP	2	608	818	8.4
Tri-37	Passenger	8:45 AM	West	8	P40-HEP	2	608	818	8.4
Tri-38	Passenger	8:47 AM	East	8	F59PH	2	300	676	20.2
Tri-39	Passenger	9:00 AM	West	8	P40-HEP	2	608	818	8.4
Tri-40	Loaded Coal	9:00 AM	East	120	SD70MAC	2	17,160	6748	0.4
Tri-41	Passenger	9:02 AM	East	8	F59PH	2	300	676	20.2
Tri-42	Passenger	9:20 AM	West	8	P40-HEP	2	608	818	8.4
Tri-43	High-Priority Merchandise	9:30 AM	West	70	SD70MAC	2	5,110	4,558	1.3
Tri-44	Loaded Coal	9:30 AM	East	120	SD70MAC	2	17,160	6,748	0.4
Tri-45	Passenger	9:32 AM	East	8	F59PH	2	300	676	20.2
Tri-46	Passenger	9:40 AM	West	8	P40-HEP	2	608	818	8.4
Tri-47	Passenger	9:45 AM	East	8	F59PH	2	300	676	20.2

Train ID	Type	Departure Time	Entry Point	No. of Cars	Locomotive Type	No. of Loco-motives	Gross Weight (tons)	Total Length (ft.)	P/W Ratio
Tri-48	Passenger	10:00 AM	East	8	F59PH	2	300	676	20.2
Tri-49	Passenger	10:05 AM	West	8	P40-HEP	2	608	818	8.4
Tri-50	Passenger	10:20 AM	East	8	F59PH	2	300	676	20.2
Tri-51	Passenger	10:24 AM	West	8	P40-HEP	2	608	818	8.4
Tri-53	Loaded Coal	10:30 AM	East	120	SD70MAC	2	17,160	6,748	0.4
Tri-52	Loaded Coal	10:30 AM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-54	Passenger	10:40 AM	East	8	F59PH	2	300	676	20.2
Tri-55	Loaded Grain	10:45 AM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-56	Passenger	10:50 AM	West	8	P40-HEP	2	608	818	8.4
Tri-58	Passenger	11:00 AM	East	8	F59PH	2	300	676	20.2
Tri-57	Passenger	11:00 AM	West	8	P40-HEP	2	608	818	8.4
Tri-59	Loaded Coal	11:00 AM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-60	Passenger	11:20 AM	East	8	F59PH	2	300	676	20.2
Tri-61	Passenger	11:40 AM	East	8	F59PH	2	300	676	20.2
Tri-62	Passenger	12:20 PM	East	8	F59PH	2	300	676	20.2
Tri-63	Passenger	12:50 PM	East	8	F59PH	2	300	676	20.2
Tri-64	Passenger	1:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-65	Passenger	1:20 PM	East	8	F59PH	2	300	676	20.2
Tri-66	Passenger	2:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-67	Loaded Coal	2:10 PM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-68	Loaded Grain	2:10 PM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-69	Passenger	2:20 PM	East	8	F59PH	2	300	676	20.2
Tri-70	Passenger	2:30 PM	West	8	P40-HEP	2	608	818	8.4
Tri-71	Passenger	2:40 PM	East	8	F59PH	2	300	676	20.2
Tri-72	Passenger	3:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-73	Loaded Coal	3:10 PM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-74	Loaded Grain	3:10 PM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-75	Passenger	3:20 PM	East	8	F59PH	2	300	676	20.2
Tri-76	Loaded Grain	3:45 PM	East	100	SD40-2	3	11,000	5,706	0.7
Tri-77	Passenger	3:50 PM	East	8	F59PH	2	300	676	20.2
Tri-78	Loaded Coal	3:50 PM	West	120	SD70MAC	2	17,160	6,748	0.4
Tri-79	Passenger	4:00 PM	West	8	P40-HEP	2	608	818	8.4
Tri-80	Passenger	4:05 PM	East	8	F59PH	2	300	676	20.2
Tri-81	Passenger	4:20 PM	East	8	F59PH	2	300	676	20.2
Tri-82	Passenger	4:38 PM	East	8	F59PH	2	300	676	20.2
Tri-84	Passenger	5:00 PM	East	8	F59PH	2	300	676	20.2
Tri-83	Passenger	5:00 PM	West	8	P40-HEP	2	608	818	8.4

Train ID	**Type**	**Departure Time**	**Entry Point**	**No. of Cars**	**Locomotive Type**	**No. of Loco-motives**	**Gross Weight (tons)**	**Total Length (ft.)**	**P/W Ratio**
Tri-85	Passenger	5:15 PM	East	8	F59PH	2	300	676	20.2
Tri-86	Passenger	5:25 PM	East	8	F59PH	2	300	676	20.2
Tri-87	Passenger	5:45 PM	East	8	F59PH	2	300	676	20.2
Tri-88	Loaded Grain	5:55 PM	East	100	SD40-2	3	11,000	57,06	0.7
Tri-89	Unit (other than coal or grain)	5:55 PM	West	110	SD70MAC	2	10,450	6,748	0.6
Tri-90	Passenger	6:10 PM	East	8	F59PH	2	300	676	20.2
Tri-91	Passenger	6:25 PM	West	8	P40-HEP	2	608	818	8.4
Tri-92	Vehicle	6:25 PM	East	60	SD70	3	7,200	5,322	1.4
Tri-93	Merchandise	6:35 PM	West	90	C44-9	2	7,650	5,996	1.1
Tri-94	Passenger	6:40 PM	East	8	F59PH	2	300	676	20.2
Tri-95	Merchandise	7:00 PM	East	80	SD70MAC	2	6,800	5,348	1
Tri-96	Passenger	7:10 PM	East	8	F59PH	2	300	676	20.2
Tri-97	Merchandise	7:30 PM	East	80	SD70MAC	2	6,800	5,348	1
Tri-98	Merchandise	7:35 PM	West	90	C44-9	2	7,650	5,996	1.1
Tri-99	Passenger	7:40 PM	East	8	F59PH	2	300	676	20.2
Tri-100	Passenger	7:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-101	Passenger	8:05 PM	East	8	F59PH	2	300	676	20.2
Tri-102	Empty Coal	8:10 PM	East	80	C44-AC	2	2800	4,546	3
Tri-103	Empty Grain	8:35 PM	West	100	SD40-2	3	3500	5,706	2.2
Tri-104	Passenger	8:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-105	Passenger	9:30 PM	East	8	F59PH	2	300	676	20.2
Tri-106	Passenger	9:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-107	Passenger	10:50 PM	West	8	P40-HEP	2	608	818	8.4
Tri-108	Passenger	11:00 PM	East	8	F59PH	2	300	676	20.2
Tri-109	Passenger	11:30 PM	East	8	F59PH	2	300	676	20.2
Tri-110	Passenger	11:50 PM	West	8	P40-HEP	2	608	818	8.4

Dense Urban Area Scenario Configuration

TTCI prepared the DUA network model based on actual railroad tracks from multiple subdivisions that operate in the downtown Chicago area. The model includes signaled single-, double-, triple- and quadruple-track territories, as well as terminals and yards and their interconnections. The subdivisions used as reference were the following:

- Metra – Joliet: from MP 0 to MP 8.4
- Metra – Southwest: from MP 0.9 to MP 9.4
- Amtrak – Union Station: from MP 0 to MP 2.4
- BNSF – Chicago: from MP 0 to MP 3.6
- BRC – Kenton Line: from MP 14 to MP 17.5
- CN – Joliet: from MP 3.7 to MP 5
- CN – Freeport: from MP 1.6 to MP 5.6
- CN – SCAL: from MP 97.4 to MP 99.2
- NS – Ashland: from MP 0 to MP 2.8
- NS – Chicago District: from MP 513.5 to MP 515.3
- NS – Chicago Line: from MP 515.7 to MP 518.6
- UP – Rockwell: from MP 98.7 to MP 99.2
- UP – Villa Grove: from MP 8.8 to MP 9.9, and from MP 98.9 to MP 99.831 (Canal St. Yard)

The terminal/yards included in the model were the following:

- BNSF – Western Avenue Yard
- CN - Bridgeport Yard
- UP – IMX IM Yard
- UP – Canal St. yard
- NS – Ashland Yard
- BRC – EW3 Storage
- Metra – Joliet Sub Yard

TTCI also added the signaling system configuration of the tracks in the model and the train schedule of all railroads that operate in the DUA area.

Figure 42 shows a schematic diagram of the RTC model created for the DUA operational scenario.

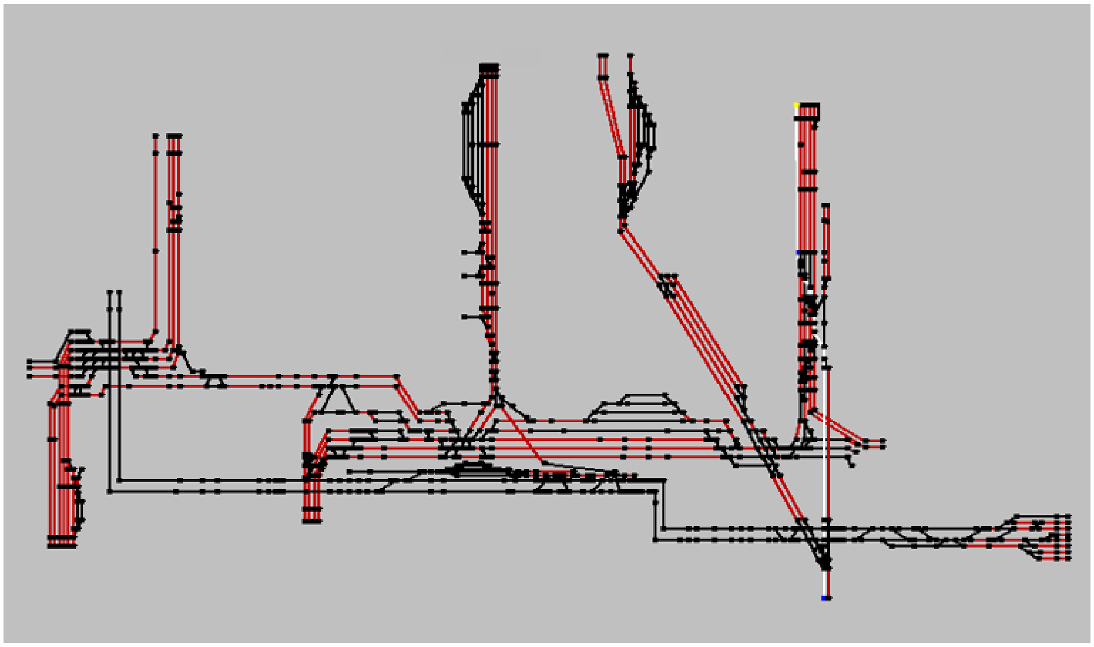


Figure 42. Schematic Diagram of the DUA Operational Scenario RTC Model

Table 20 shows the details of the track configuration for the DUA model.

Table 20. DUA Configuration Parameters

DUA Configuration Summary	
Length (mi)	43.5
Number of Crossovers	30
Number of sidings	3
Spacing between crossovers (min., max., avg. miles)	N/A
Crossovers type	Single and double
Track circuit length (min., max., avg. miles)	N/A
Number of permissive signals	56
Number of absolute signals	218
Elevation (min., max. feet)	589 , 630
Degree of curvature (min., max. degrees)	0 , 4.0
Switch type	Variable
Frog number of the switches	Variable
Type of train control	C.T.C.
Maximum speed (passenger, freight mph)	Variable

The baseline DUA model includes 1,134 trains that were configured based on actual train schedules. The schedule includes 518 trains on the busiest day of the week and 246 trains on the quietest day. Table 21 displays the number of trains per weekday that were configured in the DUA model divided into three train groups: passenger (includes Amtrak and commuter trains); expedited (includes intermodal, excess dimension, and premium intermodal trains), and freight (includes all merchandise, vehicle, local, and unit trains).

Table 21. Total Trains per Weekday in the DUA Model

Trains per Day on DUA Scenario							
	Monday	Tuesday	Wednesday	Thursday	Friday	Saturday	Sunday
Passenger	345	347	343	343	343	93	77
Expedited	96	101	97	96	100	105	98
Freight	69	64	78	69	69	58	71
TOTAL	510	512	518	508	512	256	246

Non-Signaled Territory Scenario Configuration

TTCI configured the non-signaled territory model with the same geometric characteristics as the signaled single-track model; i.e., the same number, length, and spacing of sidings; elevation; and curvature configuration. The main differences between the two models are the type of train control, type of sidings and switches, and the MAS.

Table 22 shows the details of the configuration for the non-signaled territory model.

Table 22. Non-Signaled Territory Configuration Parameters

Non-Signaled Summary Configuration	
Length (miles)	204
Number of sidings:	21
Length of sidings (min., max., avg. miles)	1.1 , 2.1 , 1.738
Spacing between sidings (min., max., avg. miles)	4.4 , 11.5 , 7.614
Sidings type	Uncontrolled
Track circuit length (min., max., avg. miles)	N/A
Number of permissive signals:	N/A
Number of absolute signals:	N/A
Elevation (min., max. feet):	720 , 1210
Degree of curvature (min., max. degrees)	0 , 6.05
Switch type	Manual without any lock
Frog number of the switches	16
Type of train control	Track warrant
Maximum speed (passenger, freight mph)	60, 50

The model was configured with 22 trains daily trains, distributed as follows: 5 local, 4 passenger, 3 loaded grains, 2 merchandise, 2 empty grains, 2 high priority merchandise, 2 UPS freight, 1 foreign, and 1 intermodal stack. Sixty percent of the trains depart from one end of the track and the rest from the other end of the track.

Table 23 shows the train schedule and consist configuration of the non-signaled territory model.

Table 23. Signaled Triple-Track Train Schedule

Train ID	Type	Departure Time	Entry Point	No. of Cars	Loco-motive Type	No. of Loco-motives	Gross Weight (tons)	Total Length (ft)	P/W Ratio
Amtrak-01	Amtrak	7:30 AM	East	8	F59PH	2	300	676	20.2
Local-01	Local	7:40 AM	East	60	SD40-2	6	5400	4313	2.8
Amtrak-02	Amtrak	7:40 AM	West	8	P40-HEP	2	608	818	8.4
LoadedGrain-01	Loaded Grain	8:55 AM	East	100	SD40-2	3	11000	5706	0.7
Merchandise-01	Merchandise	9:05 AM	West	90	C44-9	2	7650	5996	1.1
Local-02	Local	9:30 AM	West	60	SD40-2	6	5400	4313	2.8
EmptyGrain-01	Empty Grain	10:20 AM	East	100	SD40-2	3	3500	5706	2.2
LoadedGrain-02	Loaded Grain	10:30 AM	West	100	SD40-2	3	11000	5706	0.7
UPS-01	UPS Freight	11:45 AM	East	50	SD70 MAC	2	4400	3298	1.5
HPM-01	High-Priority Merchandise	11:55 AM	West	70	SD70 MAC	2	5110	4558	1.3
Local-03	Local	12:45 PM	East	60	SD40-2	6	5400	4313	2.8
Amtrak-03	Amtrak	1:00 PM	West	8	P40-HEP	2	608	818	8.4
Merchandise-02	Merchandise	1:10 PM	East	80	SD70 MAC	2	6800	5348	1
Amtrak-04	Amtrak	2:20 PM	East	8	F59PH	2	300	676	20.2
IS-01	Intermodal Stack	2:25 PM	West	70	SD70 MAC	3	6300	5122	1.6
EmptyGrain-02	Empty Grain	3:50 PM	West	100	SD40-2	3	3500	5706	2.2
Foreign-01	Foreign	5:15 PM	West	90	C44-9	2	7650	5996	1.1
Local-04	Local	6:00 PM	West	60	SD40-2	6	5400	4313	2.8
LoadedGrain-01	Loaded Grain	6:40 PM	West	100	SD40-2	3	11000	5706	0.7
Local-05	Local	7:25 PM	East	60	SD40-2	6	5400	4313	2.8
HPM-02	High-Priority Merchandise	8:05 PM	West	70	SD70 MAC	3	6300	5122	1.6
UPS-02	UPS Freight	9:30 PM	West	50	SD70 MAC	2	4400	3298	1.5

Appendix B: Track Utilization Level

Foundation Concepts

Track utilization level (TUL) defines the volume of traffic in a portion of territory compared to its capacity to assess congestion levels.

The capacity of a rail corridor or subdivision is defined as the maximum volume or number of trains per day that the infrastructure can accommodate without compromising the safety or reliability of the flow of trains. The capacity of a rail line is affected by many factors, including the number of tracks, frequency and length of sidings, capacity of the yards and terminals along a corridor to receive the traffic, type of control systems, terrain, mix of train types, power of the locomotives, track speed, and individual railroad operating practices.

TTCI used the National Rail Freight Infrastructure Capacity and Investment (NRFICI) Study [3] as a reference to determine railroad capacity and TUL. According to this study, the rail capacity can take two forms: the *theoretical capacity* is the maximum number of trains assuming perfect conditions; the *practical capacity* considers factors such as possible disruptions, maintenance, human decisions, weather, possible equipment failures, supply and demand imbalances, and seasonal demand. Practical capacity is about 70 percent of the theoretical capacity and provides reliable service. The theoretical capacity is obtained based on the results of the simulation of the operational scenarios.

However, translating the definition of capacity to practical numbers may be a subjective task because the perception of an affectation to safety or reliability of the train flow may vary depending on the situation or the viewer. For practical purposes of this project to have an objective threshold to define capacity, the capacity of a scenario will be determined as the number of trains per day that can run on the scenario that achieve the maximum number of train-miles per day.

The definition of the maximum number of train-miles per day as threshold is based on the following reasoning: if the number of trains per day is increased in a scenario, then the number of train-miles per day will also increase thus the delay due to the rise in the number of conflicts that need to be solved. However, there will be a maximum number of train-miles per day that can be achieved; beyond that point, train-miles per day will start decreasing as the number of trains per day increases, since the delay effects will have surpassed the effects of the number of trains rise.

Practical Capacity and TUL Calculation Methodology

The calculation of the practical capacity depends on two main parameters: 1) the characteristics of the territory (e.g., single- or multiple-track, signaled or non-signaled, number of tracks), and 2) the mix of train types (e.g., freight, passenger) that operate in the corridor.

The NRFICI study explains that the mix of trains is an important factor when determining the capacity of a rail line. A corridor that serves a single type of train will usually accommodate more trains per day than a corridor that serves a mix of train types since trains of the single type can be operated at similar speeds and with more uniform spacing between the trains due to similar braking capabilities.

The NRFICI study also introduces a method to adjust for different mixes of trains. Each operational scenario is assigned a lower and an upper boundary for the maximum number of trains. The lower boundary is defined as the maximum number of trains per day assuming an equal mix of merchandise bulk, intermodal-auto, and passenger trains (one-third each). The upper boundary is defined as the maximum number of trains per day, assuming 100 percent one type, and 0 percent of the other two types (complete homogeneity). To move between the lower and upper boundaries, the standard deviation of the train mix is used to scale the range between them. For a train mix of 33 percent, 33 percent, and 33 percent for each of the three types, the standard deviation is zero; therefore, a zero adjustment is added to the lower boundary. A train mix of 100 percent, 0 percent, and 0 percent yields a standard deviation of 0.47, which is scaled to produce a factor that added to the lower boundary equaled the upper boundary. A standard deviation falling between the minimum of zero and the maximum of 0.47 produced a capacity somewhere between the lower and upper boundaries.

The calculation of the practical capacity was conducted per the following steps:

1. For each operational scenario, TTCI developed RTC simulation runs with on type of train (High-Priority Merchandise) and calculated the theoretical capacity of the scenario which includes the following steps:
   a. The process begins running a simulation with the initial number of trains configured to depart at evenly spaced intervals throughout the day, although their departing time is affected by a randomization process that may anticipate or delay the departure in up to 30 minutes. Fifty percent of the trains will start from one end of the track and the rest of trains from the opposite end. Once the simulation ends, the results are compiled and the number of train-miles per day is obtained after processing one of the simulator's output files.
   b. Next, the number of trains per day is increased, and the process is repeated until the maximum value of train-miles per day is found. The number of trains per day that corresponds to the maximum value of train-miles per day stablishes the theoretical capacity of the scenario.
2. Based on the theoretical capacity, TTCI calculated the practical capacity (70 percent of theoretical capacity).
3. The practical capacity calculated for a single train type was converted to capacity values of cases with multiple types of trains, using the method described in the NRFICI study [1].

Table 24 shows the practical capacity figures per operational scenario, as calculated in the NRFICI study [1].

Table 24. Practical Capacity Values per Operational Scenario

Operational Scenario	Practical Capacity (Trains per Day)	
	Mixed Train Types	Single Train Type
Signaled Single-track	30	48
Signaled Double-track	75	100
Signaled Triple-track	133	163
Non-signaled	16	20

The proceeding sections describe the practical capacity calculations made for each operational scenario using RTC simulations and how they compare with the values from Table 24.

Practical Capacity of the Signaled Single-Track Scenario

TTCI used the total train-miles per day as the parameter to define the practical capacity of the scenario. The initial number of daily trains was established at 56. Table 25 shows the results of the simulations. Based on the number of train-miles per day, the theoretical capacity is reached with 68 trains per day as highlighted in green. The practical capacity results in a value of 48 trains per day (70 percent of 68) for a single train, which matches the number shown in Table 24 for the signaled single-track operational scenario.

Table 25. Results of RTC Runs for the Signaled Single-Track Theoretical Capacity Calculation

Theoretical Signaled Single-Track Capacity Runs (RTC)			
Train count per day	**Headway (min)**	**Average speed (mph)**	**Total Train-miles per day**
56	51	39.904	11,204.00
60	48	38.206	11,897.83
62	47	33.072	11,616.05
64	45	31.756	12,050.39
65	44	27.587	11,553.59
66	43	29.465	12,029.47
67	42	27.084	11,785.71
68	42	26.59	**12,072.65**
70	41	23.342	11,541.78
72	40	18.677	10,555.38

The mix of trains originally configured for the signaled single-track scenario is composed of four passenger trains (24 percent), five expedited trains (29 percent), and eight freight trains (47 percent) – which results in a standard deviation of 0.09998. Based on the standard deviation, the practical capacity for this mix of trains in the signaled single-track results in 34 trains per day. Table 26 summarizes the calculations of practical capacity and TUL for this scenario.

Table 26. Practical Capacity Summary for the Signaled Single-Track Operational Scenario

Type of Train	Single Type of Train	Mix of Trains of the Scenario			
TUL	Practical Capacity (100 percent TUL)	Practical Capacity (100 percent TUL)	75 percent TUL	50 percent TUL	25 percent TUL
Number of Trains per Day	48	34	26	17	9

Practical Capacity of the Triple-Track Operational Scenario

TTCI used the same method applied to determine the capacity of the signaled single-track scenario to determine the practical capacity of the signaled triple-track scenario. The initial number of trains, 242, was gradually increased to 262 trains per day. RTC was unable to resolve the case with higher number of trains due to the increasing number of conflicts that were being generated during the simulations. TTCI made more than 40 attempts of simulation with 264 trains per day, each with different seed numbers for the randomization process, but RTC failed to complete the runs. TTCI held conference calls with Berkeley Simulations to review the issues found and it was concluded that the model had reached the maximum number of feasible daily trains that could be dispatched. This number – 262 trains per day – was considered the theoretical capacity for this scenario. Table 27 shows the results of the practical capacity simulation runs performed for this scenario.

Table 27. Results of RTC Runs for the Signaled Triple-Track Theoretical Capacity Calculation

Theoretical Signaled Triple-Track Capacity Runs (RTC)			
Train count per day	Headway (min)	Average speed (mph)	Total Train-miles per day
242	13:35	39.54	25,102.33
246	13:20	38.54	25,521.38
250	13:05	38.47	25,780.64
254	12:51	38.39	26,270.94
258	12:37	37.61	26,503.99
262	12:24	37.10	27,057.19

The practical capacity for the triple-track scenario for a single type of train resulted in 183 trains per day (70 percent of 262 trains). This number is slightly higher than what is shown in Table 24 (163 trains per day for signaled triple-track), but the difference between both numbers is acceptable as the results in the NRTC study represent average numbers obtained from multiple lines.

The mix of trains originally configured for the signaled triple-track scenario is composed of 75 passenger trains (68 percent), 15 expedited trains (14 percent) and 20 freight trains (18 percent), which results in a standard deviation of 0.24711. The practical capacity for this mix of trains in the signaled triple-track scenario results in 159 trains per day.

Table 28 summarizes the calculations of practical capacity and TUL for this scenario.

Table 28. Practical Capacity Summary for the Signaled Triple-Track Operational Scenario

Type of Train	**Single Type of Train**	**Mix of Trains of the Scenario**			
TUL	**Practical Capacity (100 percent TUL)**	**Practical Capacity (100 percent TUL)**	**75 percent TUL**	**50 percent TUL**	**25 percent TUL**
Number of Trains per Day	183	159	120	80	40

Practical Capacity of the Signaled Double-Track and Non-signaled Territory Operational Scenarios

The practical capacity results obtained from the RTC simulation runs for the signaled single-track and triple-track operational scenarios showed results comparable to the NRFICI study practical capacity values for the same operational scenarios. As the simulation runs are extremely time-consuming, and as the project was facing budget restrictions, TTCI did not perform RTC simulation runs for the signaled double-track and non-signaled territories, but rather used the practical capacity numbers as calculated in the NRFICI study.

The practical capacity for the signaled double-track scenario with a single type of train is calculated as 100 trains per day in the NRFICI study (Table 24).

The mix of trains for the signaled double-track scenario is composed of 4 passenger trains (5 percent), 19 expedited trains (22 percent), and 63 freight trains (73 percent) – which results in a standard deviation of 0.29113. The practical capacity for this mix of trains in the signaled double-track scenario results in 81 trains per day. Table 29 summarizes the calculations of practical capacity and TUL for this scenario.

Table 29. Practical Capacity Summary for the Signaled Double-Track Operational Scenario

Type of Train	**Single Type of Train**	**Mix of Trains of the Scenario**			
TUL	**Practical Capacity (100 percent TUL)**	**Practical Capacity (100 percent TUL)**	**75 percent TUL**	**50 percent TUL**	**25 percent TUL**
Number of Trains per Day	100	81	61	41	21

The practical capacity for the non-signaled operational scenario with a single type of train is calculated as 20 trains per day in the NRFICI study, as shown in Table 24. The typical train mix for this scenario is 4 passenger trains (18 percent), 11 expedited trains (50 percent), and 7 freight trains (32 percent) – which results in a standard deviation of 0.13033. The practical capacity for this mix of trains in the non-signaled operational scenario results in 17 trains per day. Table 30 summarizes the calculations of practical capacity and TUL for this scenario.

Table 30. Practical Capacity Summary for the Non-Signaled Operational Scenario

Type of Train	Single Type of Train	Mix of Trains of the Scenario			
TUL	Practical Capacity (100 percent TUL)	Practical Capacity (100 percent TUL)	75 percent TUL	50 percent TUL	25 percent TUL
Number of Trains per Day	20	17	13	9	5

Practical Capacity of Dense Urban Area Operational Scenario

The DUA operational scenario is a complex mix of tracks that includes 13 subdivisions with interconnections between them. The subdivisions include signaled single-, double-, triple-, and quadruple-tracks. The complexity of the scenario (number of subdivisions, interconnections, different train routes, etc.) makes it very difficult if not possible to calculate the practical capacity by systematically increasing the number of trains in the overall network model until the maximum number of train miles per day is achieved. The NRFICI study does not include a capacity reference for this type of complex scenarios that could be used as a reference.

TTCI developed a method to calculate the practical capacity of a DUA where the capacity is calculated per individual sections of the entire model, which when combined, determines the practical capacity of the DUA. The DUA model contains 13 interconnected subdivisions, as shown in Figure 43.

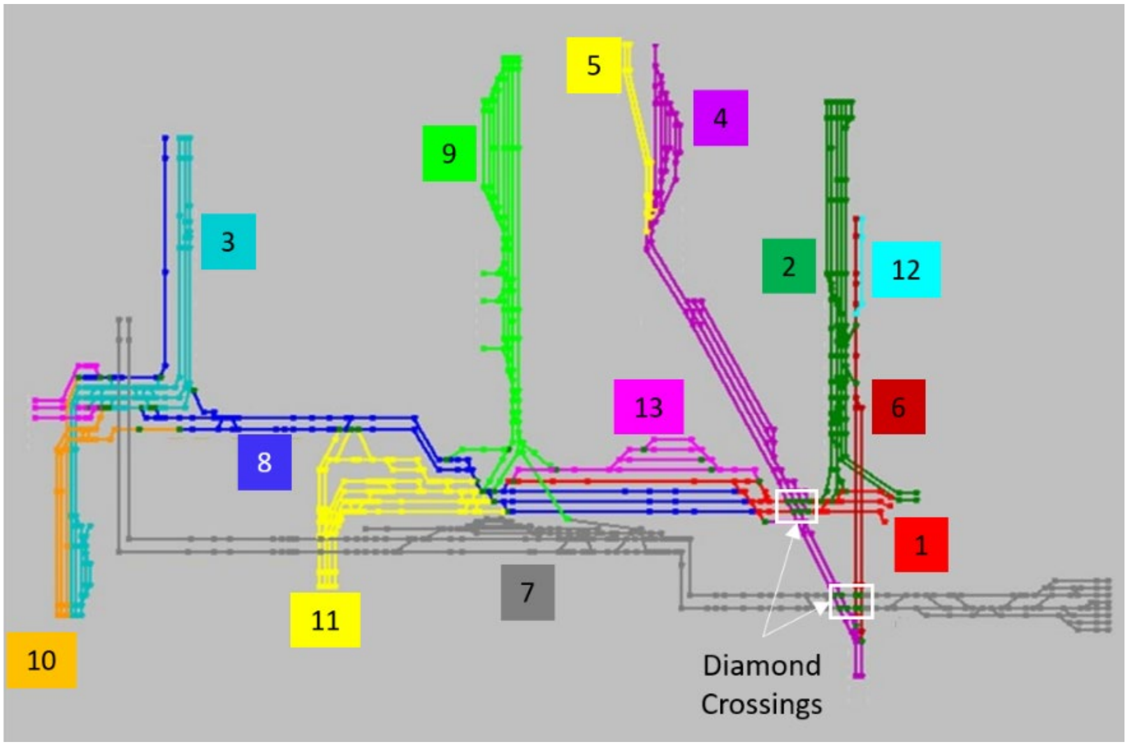


Figure 43. Schematic Diagram of Subdivisions in the DUA RTC Model

Each subdivision has several mainline tracks as shown in Table 31.

Table 31. Number of Mainline Tracks in Each DUA Subdivision

Subdivision	Number of Mainline Tracks
1	2
2	4
3	2
4	2
5	2
6	1
7	2
8	2
9	2
10	3
11	2
12	1
13	2

TTCI separated the 13 subdivisions into nine sections based on how they were connected and the train routes that operate on them. Subdivisions with multiple train routes were merged into one section. The capacity of each section was calculated separately per the NRFICI study, based on the lowest number of tracks of each subdivision included in that section. For example, Subdivisions 4 and 5 are merged and become a single section limited to the capacity of a signaled single-track, since this is the most restrictive capacity of the two merged subdivisions. Table 32 shows the theoretical and practical capacity for each the sections of the DUA, as well as the calculation for the entire DUA operational scenario (sum of all sections).

Table 32. Practical Capacity Calculation of the DUA Sections

Section	Merged Subdivisions	Number of Mainline Tracks	Practical Capacity	
			Three Types of Train Equally Distributed	Single Type of Train
1	7	2	75	100
2	4, 5	2	75	100
3	1, 8, 11	2	75	100
4	8, 10	3	133	163
5	3	2	75	100
6	13	1	30	48
7	9	2	75	100
8	2	4	248	340
9	6, 12	1	30	48
DUA (Total)			**816**	**1,099**

The sum of the practical capacity of the summarized subdivisions give a minimum (Types of Train Equally Distributed) and a maximum (Single Type of Train) practical capacity for the DUA operational scenario. This calculation, however, does not account for the capacity that is lost at diamond crossings between subdivisions.

There are two diamond crossings in the model, the first between Section 1 (Subdivision 7) and Section 9 (Subdivisions 6 and 7) and Section 2 (Subdivisions 4 and 5), and the second between Sections 2 and 3 (Subdivisions 1 and 4). Both diamond crossings are between signaled double-track lines.

The reduction of capacity (number of daily trains) is calculated by resolving the set of equations that express the frequency of trains arriving at a diamond crossing in each subdivision including the delay incurred by the diamond crossings in a day (1,440 minutes):

$$Headway1 * NTrains1 + DiamondDelay * NTrains2 = 1{,}440 \tag{8}$$

$$Headway2 * NTrains2 + DiamondDelay * NTrains1 = 1{,}440 \tag{9}$$

In Equations 8 and 9, *NTrains1* is the number of daily trains in one subdivision, while *NTrains2* is the number of daily trains in the other subdivision. Assuming that each crossing in a diamond causes 10 minutes of delay, the first diamond cross (between Sections 1 and 9) will result in:

- Number of trains per day = 75 (practical capacity for 3 types of trains equally distributed)
- Headway = 1,440/(75/2) = 38.4 minutes (in each track)

As the headway is the same in both sections, the equations become:

$$38.4 * NTrains1 + 10 * NTrains2 = 1{,}440 \tag{10}$$

$$38.4 * NTrains2 + 10 * NTrains1 = 1{,}440 \tag{11}$$

Resolving the equations, the practical capacity for equally distribution of train types in the subdivision becomes 59 instead of 75 daily trains; i.e., a reduction of 16 trains in each subdivision. The total reduction in the DUA operational scenario practical capacity due to diamond crossings is 64 trains (16 trains in each subdivision), which brings the brings the lower range of the practical capacity range down to 752 daily trains. Applying the same calculation to the single type of train, brings the higher end of the range to 995 daily trains.

The number of trains in the baseline DUA operational scenario (based on the average of train types during weekday in Table 21) is composed of 344 passenger trains (68 percent), 98 expedited trains (19 percent), and 78 freight trains (13 percent); which results in a standard deviation of 0.2404. Based on this standard deviation, the practical capacity of the DUA operational scenario is 810 trains.

TTCI analyzed the results of the RTC simulation of the baseline DUA configuration to verify how it compares with the theoretical practical capacity method presented above. The baseline DUA configuration is based on actual train traffic operation in downtown Chicago and can provide good insights of capacity; particularly at peak operation times. The number of daily trains in the baseline DUA configuration vary, as shown in Table 21. During weekdays, train traffic is higher, reaching a peak of 518 daily trains on Wednesdays, while weekends see less traffic. The traffic density varies during the day, reaching a peak 19 trains running simultaneously at any given moment. Rush hour occurs between 6:00 a.m. to 9:00 a.m., weekdays.

On Wednesdays during rush hour, 119 trains run in total; however, only 100 trains run routes long enough to have a significant effect on the capacity of the scenario. Assuming that during rush hour the model is operating at practical capacity or very close to it, the number of trains during rush hours can be extrapolated to estimate the practical capacity of the scenario for the entire day, which results in 800 trains daily (100 trains every 3 hours). This result is very close to the calculation made with the method previously presented (810 daily trains) and supports the use of those results for the DUA operational scenario analysis.

Table 33 summarizes the calculations of practical capacity and TUL for this scenario.

Table 33. Practical Capacity Summary for the DUA Operational Scenario

Type of Train	Single Type of Train	Mix of Trains of the Scenario			
TUL	Practical Capacity (100 percent TUL)	Practical Capacity (100 percent TUL)	75 percent TUL	50 percent TUL	25 percent TUL
Number of Trains per Day	995	810	608	405	203

Appendix C: Theoretical Headway Reduction Calculations

Figures 44 through 55 show the theoretical train headway calculations for each of the scenarios selected for this analysis.

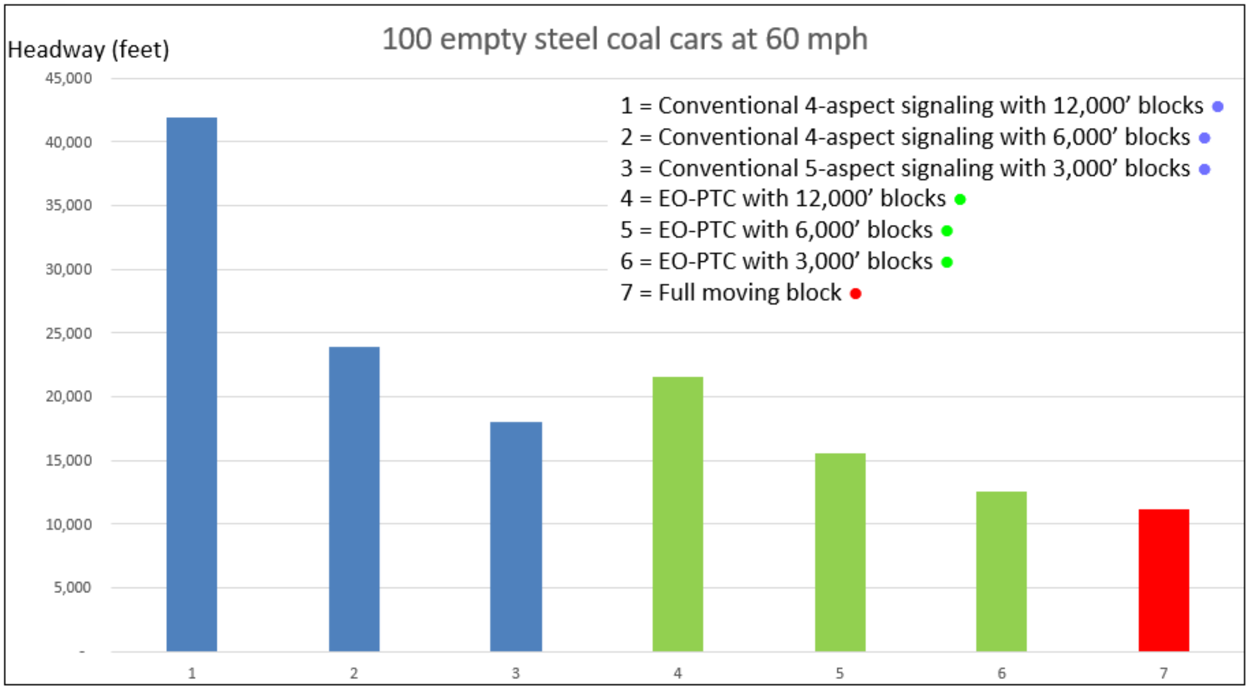


Figure 44. EO-PTC and FMB Train Headway for Empty Steel Coal Cars at 60 mph

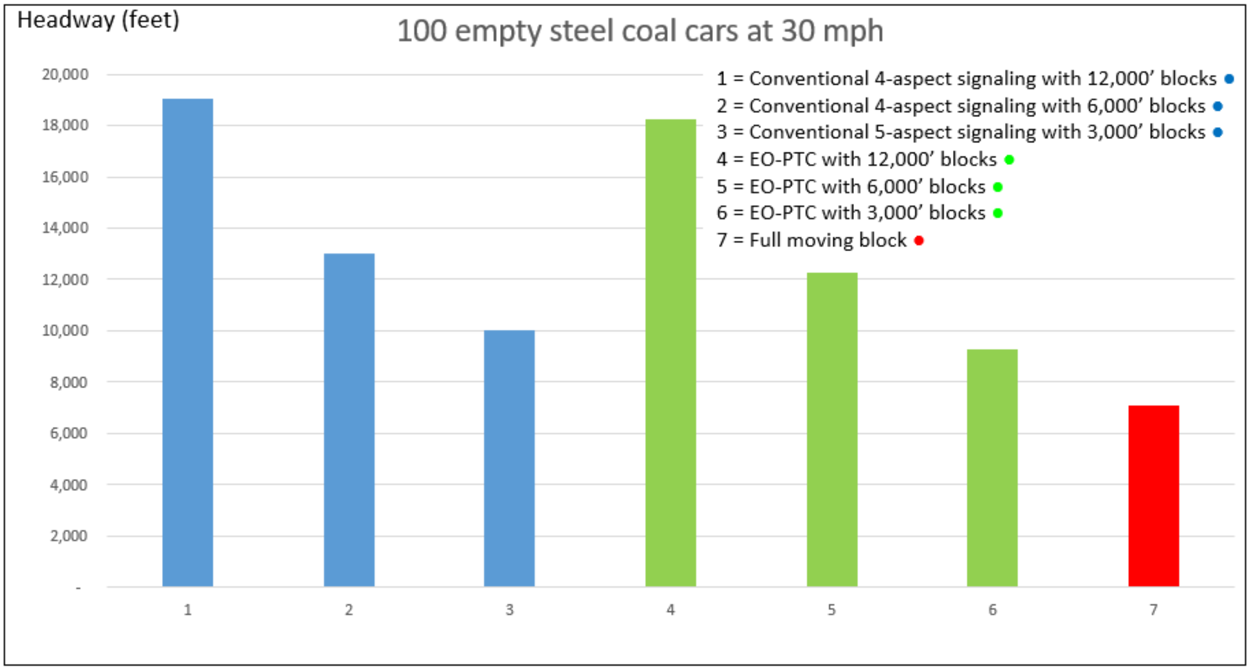


Figure 45. EO-PTC and FMB Train Headway for Empty Steel Coal Cars at 30 mph

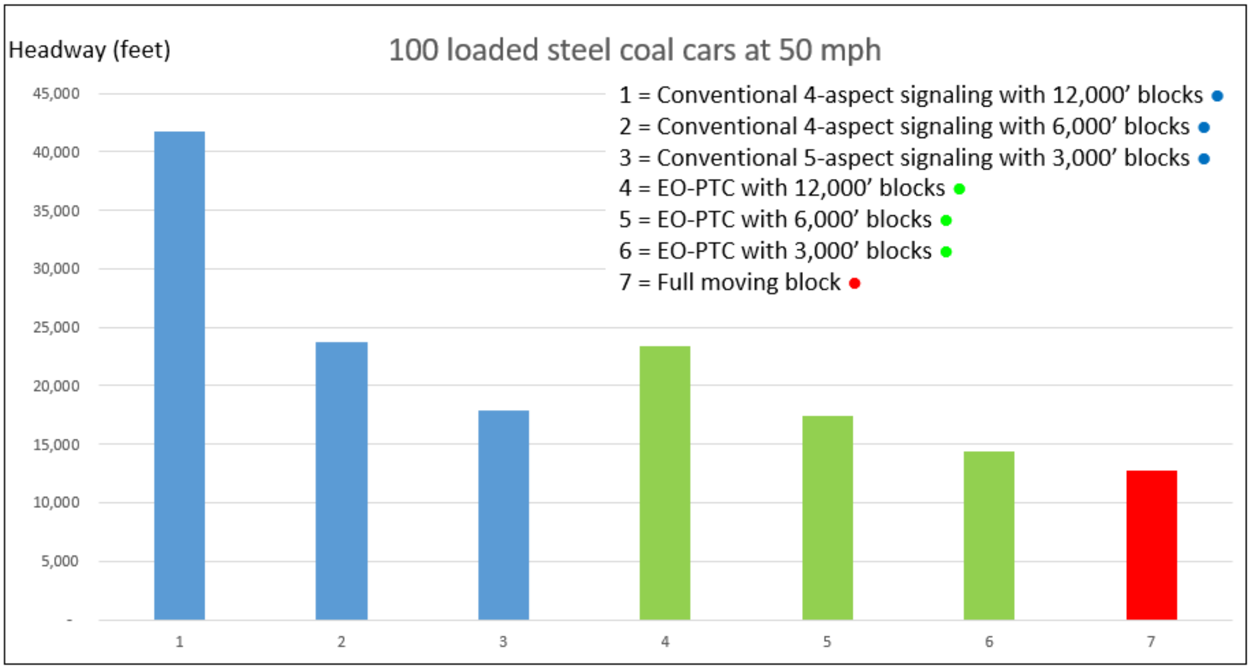


Figure 46. EO-PTC and FMB Train Headway for Loaded Steel Coal Cars at 50 mph

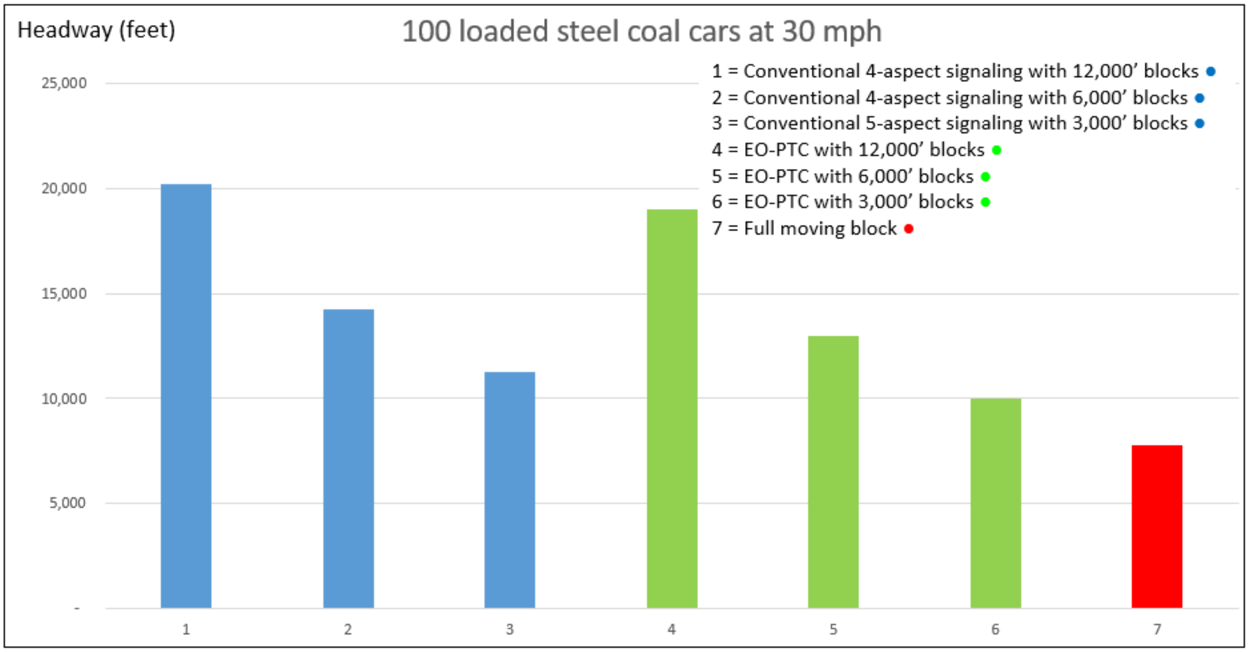


Figure 47. EO-PTC and FMB Train Headway for Loaded Steel Coal Cars at 30 mph

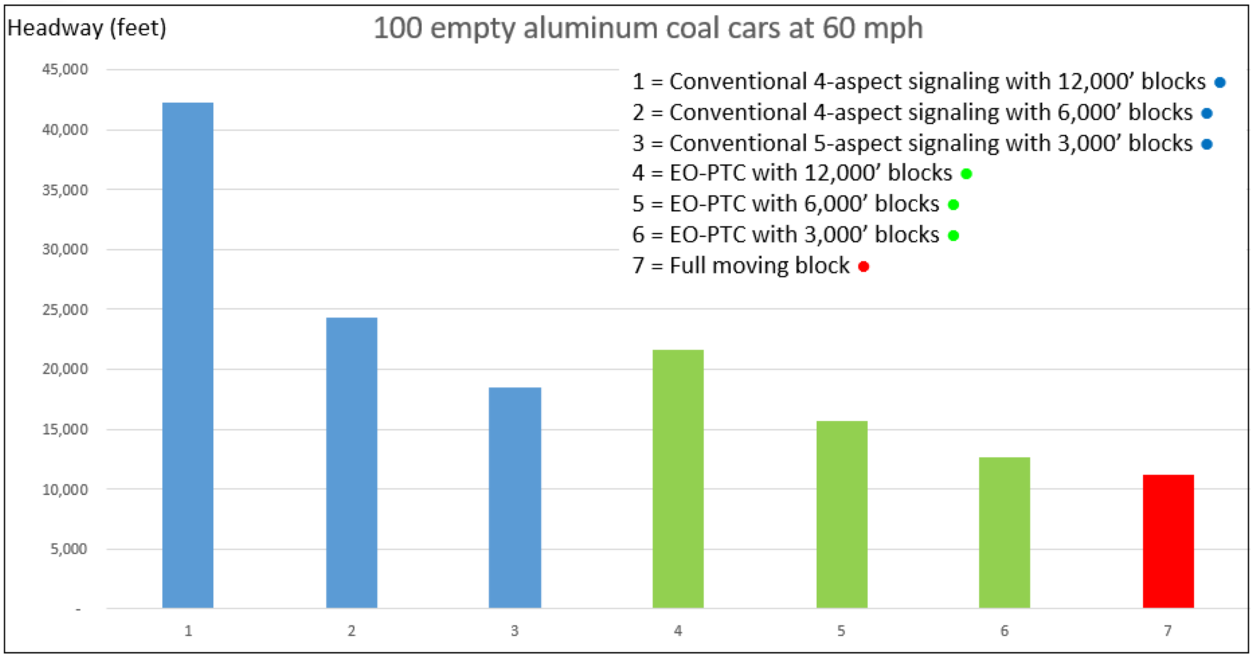


Figure 48. EO-PTC and FMB Train Headway for Empty Aluminum Coal Cars at 60 mph

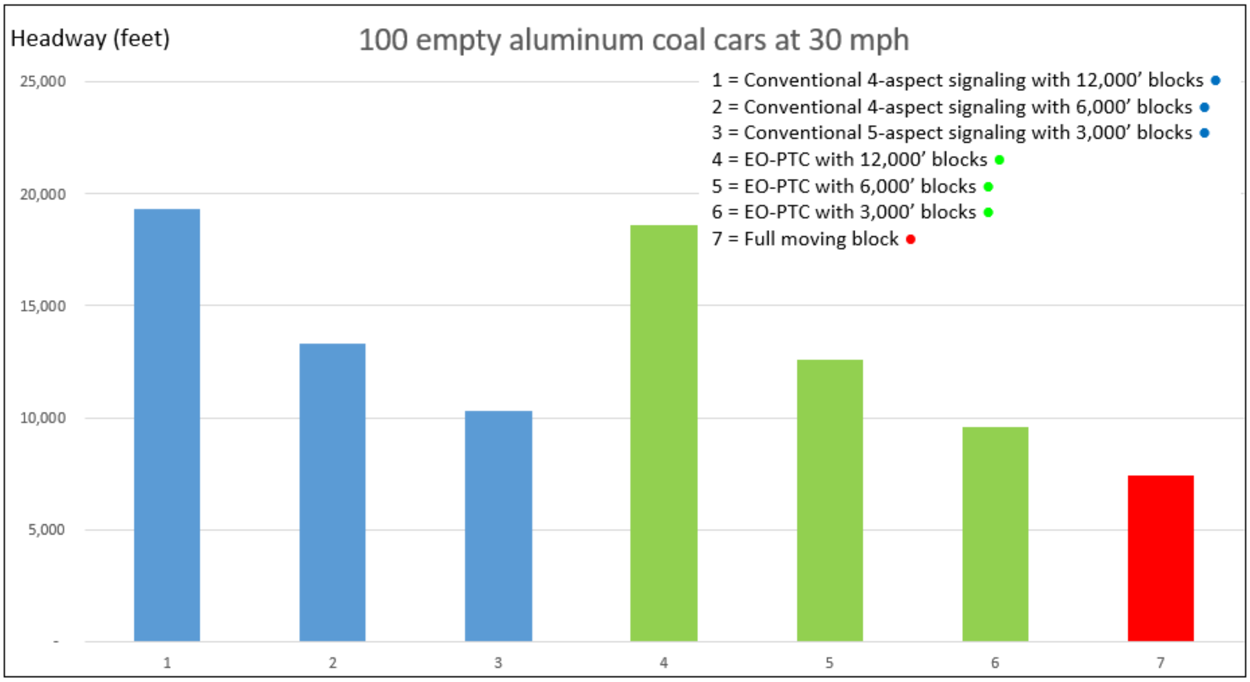


Figure 49. EO-PTC and FMB Train Headway for Empty Aluminum Cars at 30 mph

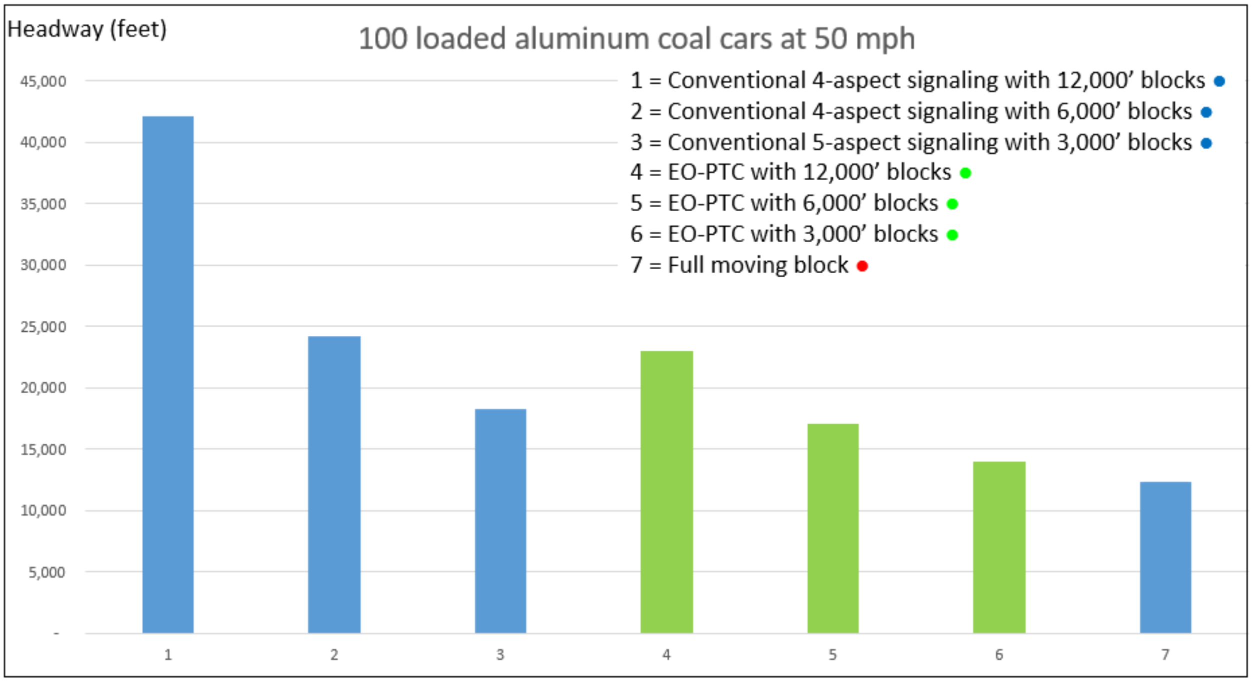


Figure 50. EO-PTC and FMB Train Headway for Loaded Aluminum Cars at 50 mph

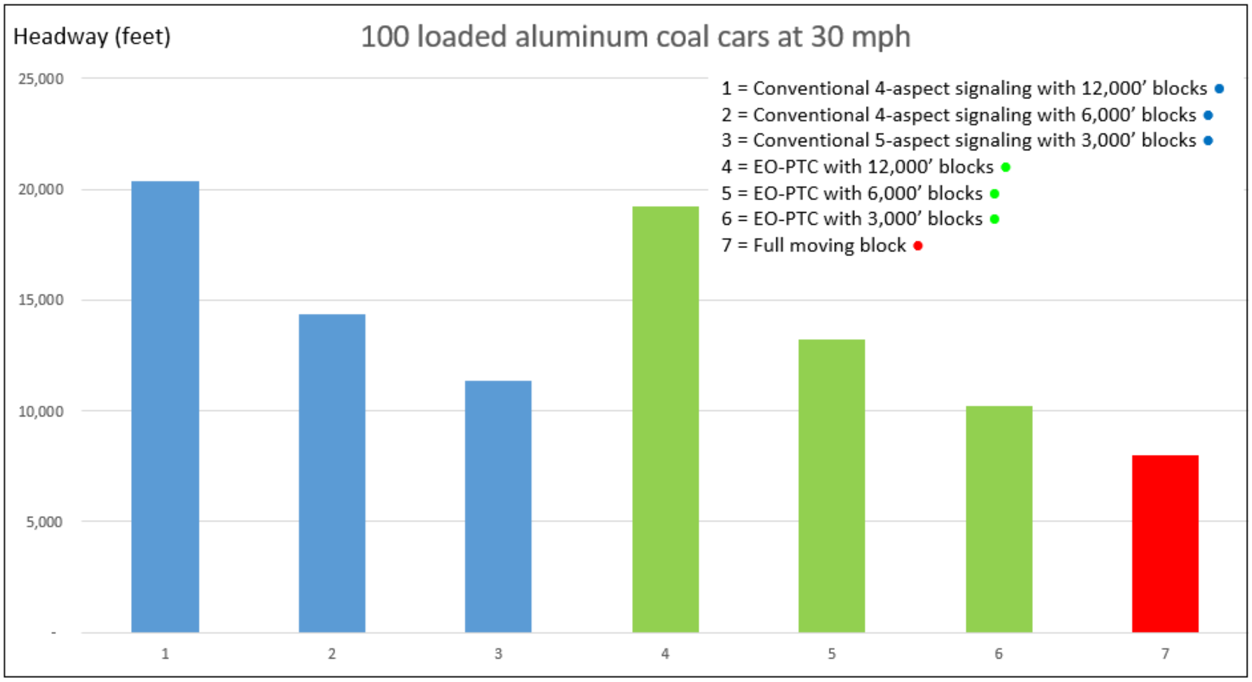


Figure 51. EO-PTC and FMB Train Headway for Loaded Aluminum Cars at 30 mph

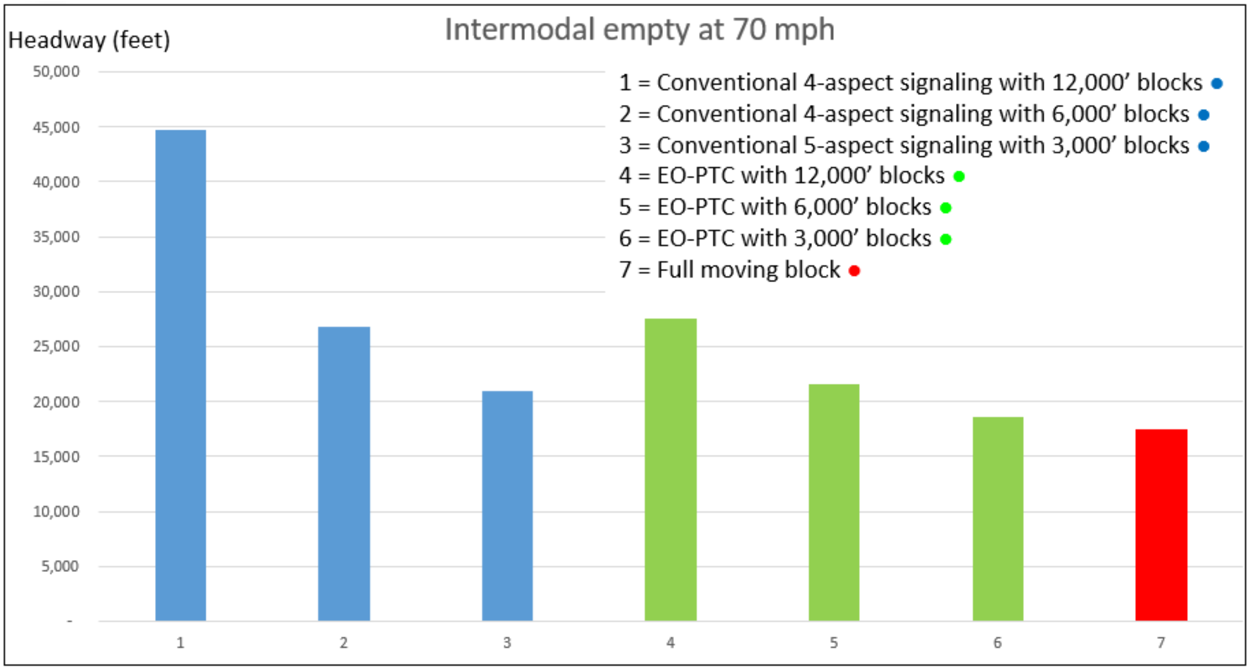


Figure 52. EO-PTC and FMB Train Headway for Empty Intermodal at 70 mph

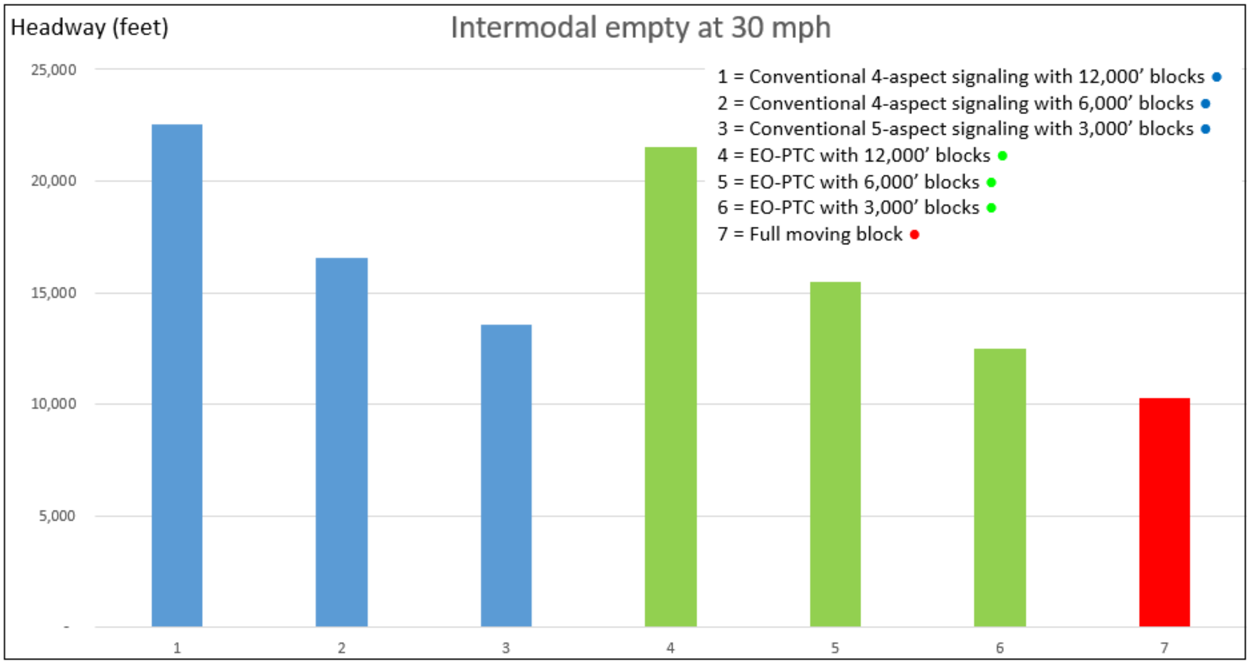


Figure 53. EO-PTC and FMB Train Headway for Empty Intermodal at 30 mph

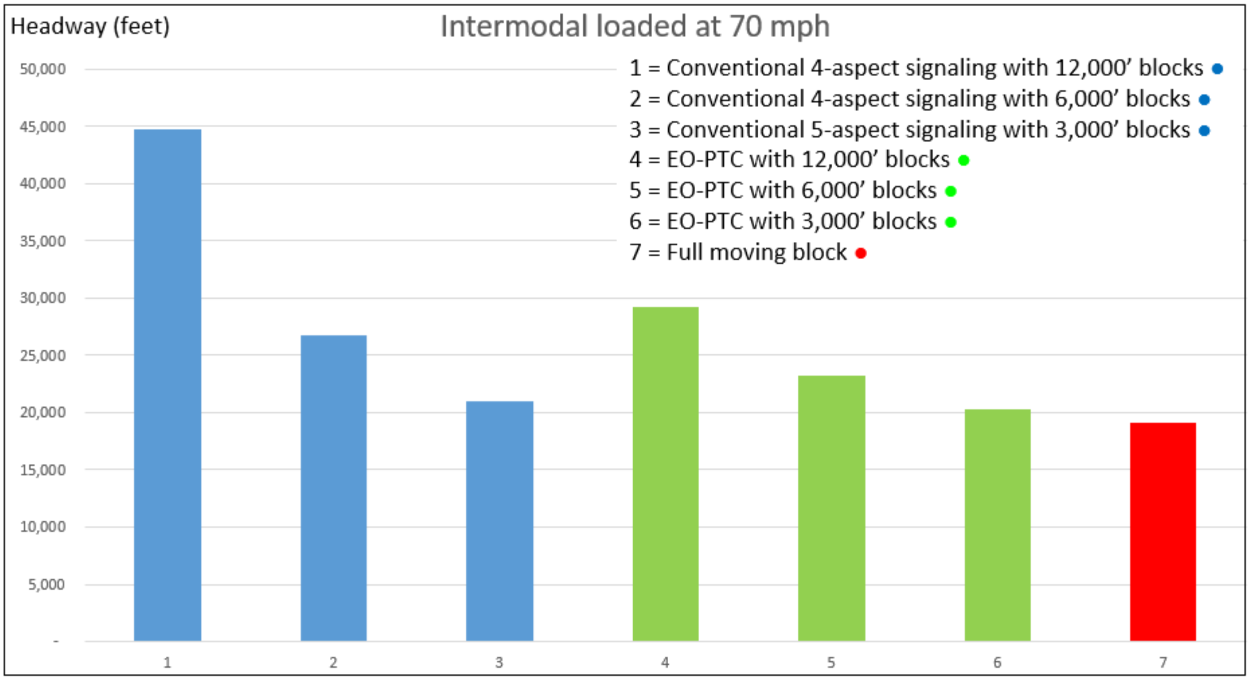


Figure 54. EO-PTC and FMB Train Headway for Loaded Intermodal at 70 mph

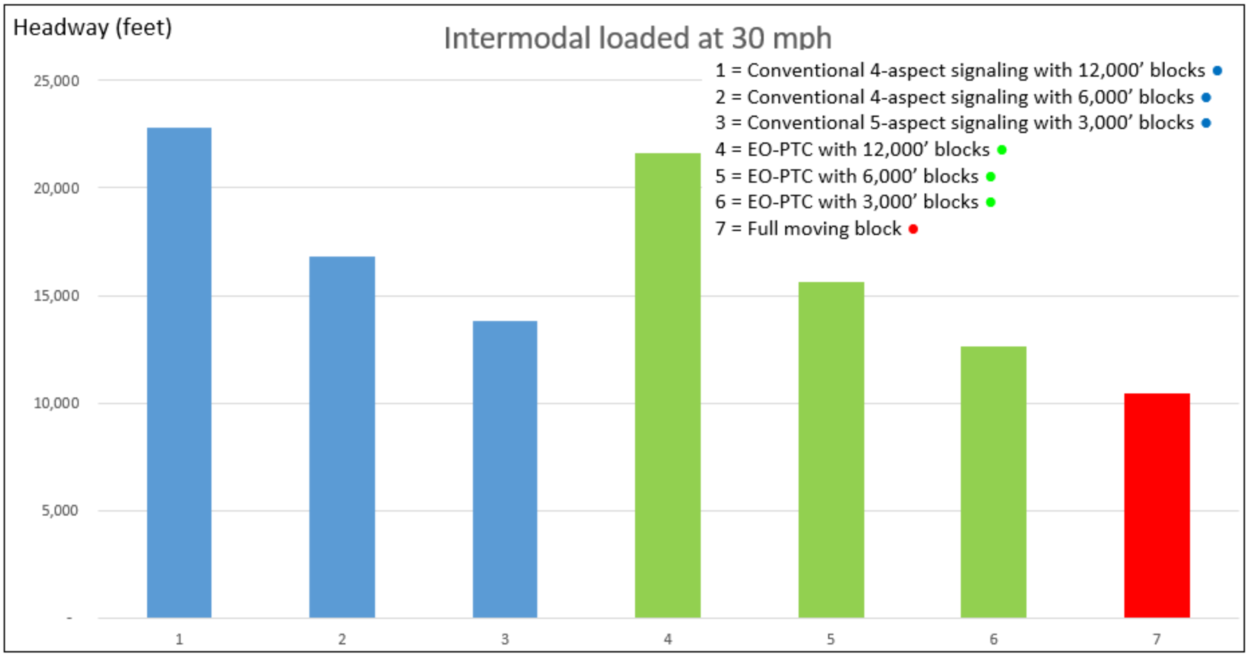


Figure 55. EO-PTC and FMB Train Headway for Loaded Intermodal at 30 mph

Appendix D: PTC Braking Rate Calculation

TTCI used the results of TOES simulations developed for multiple FRA PTC braking algorithm projects [4] to calculate the PTC target braking rates that were used in RTC simulation.

The braking rate is calculated as a linear deceleration rate between the target stopping position and the start of the simulation at the initial start speed. To simulate the locomotive engineer initiating braking to avoid PTC enforcement, using the braking enforcement warning from the onboard PTC system, the start of the simulation is calculated by adding the distance traveled by the train over a period of 20 seconds at the initial start speed to the braking distance (Figure 56).

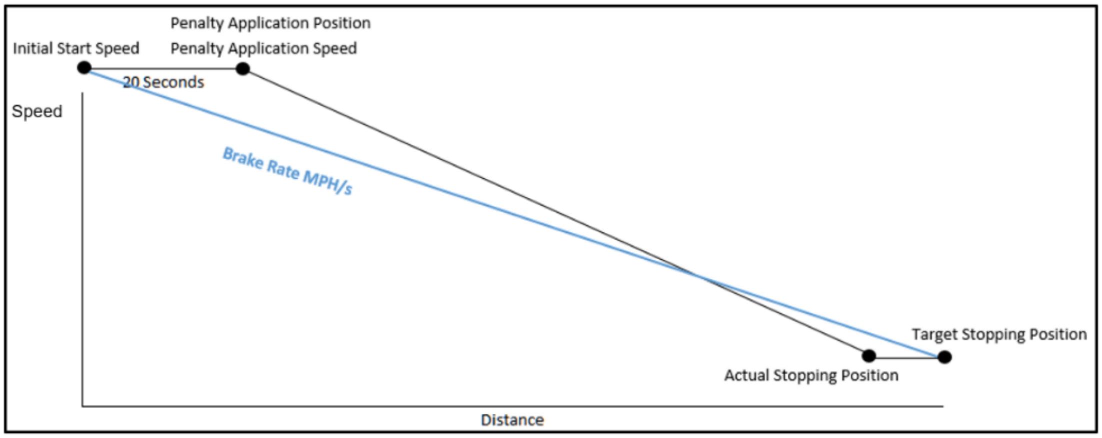


Figure 56. Braking Rate Calculation Diagram

The TOES simulations included runs with multiple grade profile inclination and initial train speeds, as shown in Table 34.

Table 34. Track Profile Inclination and Initial Train Speeds Included in the TOES Simulation Runs for Each Train Class

Train Class	Track Grade Inclination (%)	Train Speed (MPH)					
Expedited and Freight	Flat	10	30	50	60	70	
	- 0.5	10	30	50	60	70	
	+ 0.5	10	30	45	50	60	
	-1.1	10	30	45	55	60	70
	+1.5	10	15	20	25		
	-1.7	25					
	-2.2	15	20				
	-2.8	15	20				
Passenger	Flat	10	80	90			
	+0.5	10					
	-1.5	10	80	90			
	+1.5	10	80	90			

The results of the simulation runs were compiled.

Figure 57, Figure 58, and Figure 59 show the histogram of the results obtained for each of the train classes.

Note that the acceleration rate due to grade was removed from each simulation to eliminate its influence on the results. This was done because data was pulled from a large number of different simulations that simulated trains on several different grades. The acceleration rate (mph/s) due to grade force is 21.94*percent grade.

The grade force is related to the train weight and the percent grade, as shown in Equation 12.

$$F = (Weight_{lbs} * -20 * \ percentgrade)/2000 \tag{12}$$

Additionally, the grade force is equal to the mass multiplied by the acceleration as shown in Equation 13, where the train mass is in slugs, as shown in Equation 14.

$$Mass = \frac{\left(\frac{Weight_{lbs}}{32.17405ft}\right)}{s\char`^2} \tag{13}$$

$$\frac{Weight_{lbs} * -20 * percentgrade}{2000} = \frac{\left(\frac{Weight_{lbs}}{32.17405ft}\right)}{s\char`^2} * Acc \tag{14}$$

Resolving Equation 14 in mph/s, results in Equation 15, the acceleration due to the force of grade.

$$Acc = (-0.2194 * \ percentgrade)mph/s \tag{15}$$

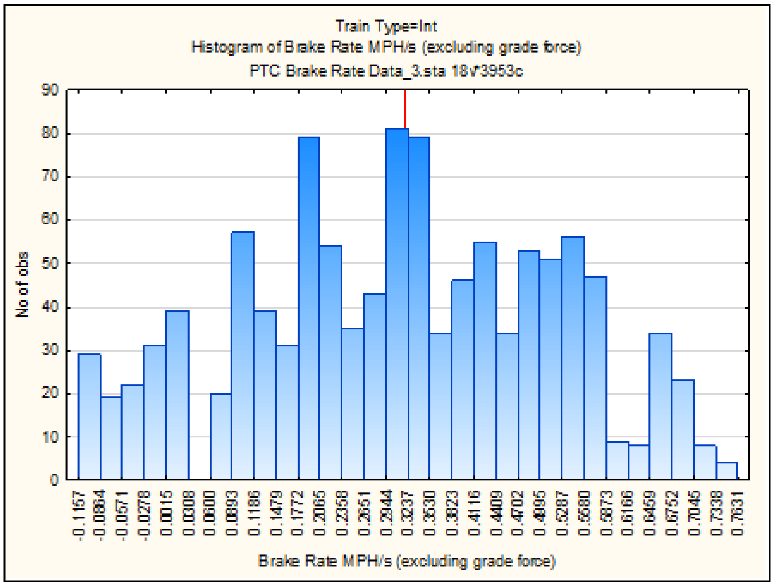


Figure 57. Histogram of Braking Rates for Train Class Expedited

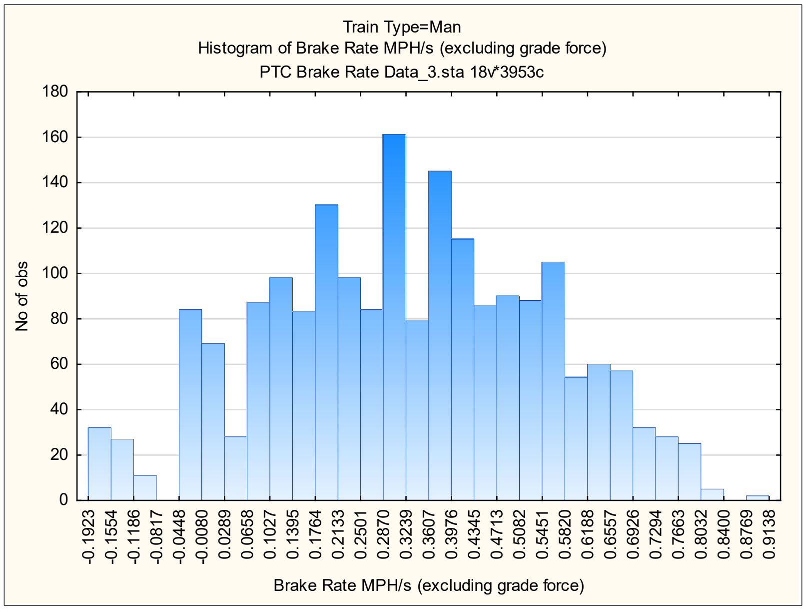


Figure 58. Histogram of Braking Rates for Train Class Freight

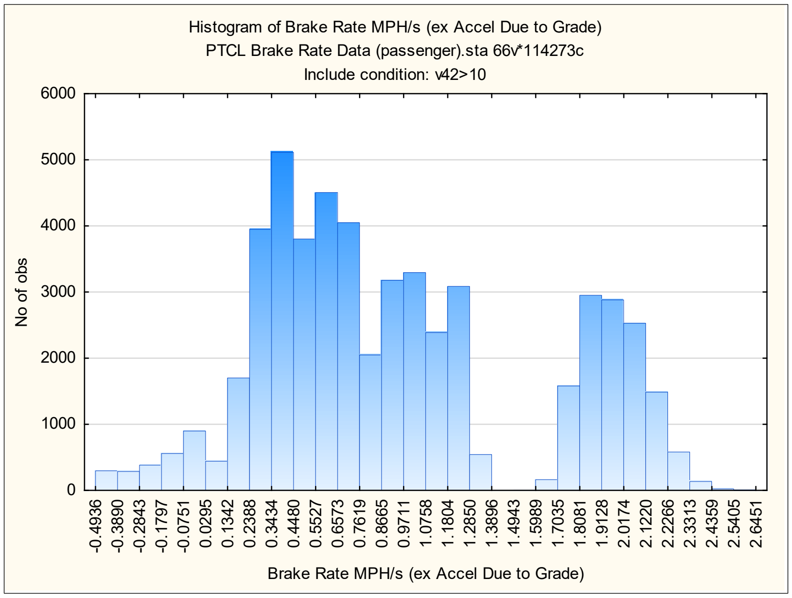


Figure 59. Histogram of Braking Rates for Train Class Freight

The median values of the braking rate results calculated for each train class are shown in Table 35. These values were used in the configuration of the Normal service application with PTC target in RTC.

Table 35. PTC Braking Rates per Train Class

Train Class	Braking Rate (mph/s)
Expedited	0.32
Freight	0.29
Passenger	1.06

Appendix E: Office-To-Locomotive Communications Link Availability

In the current overlay ITC PTC system, there are two message types sent by the back office to the locomotive that can result in impact on operations if not received by the locomotive onboard within a specified time period:

- Office Segment Poll Messages: Message sent by the back office to the train to provide information on the current set of mandatory directives and track data.
- Wayside Status Relay Service (WSRS) Messages: Wayside Status Messages (WSMs) sent by the WSRS server at the back office with the latest received status of monitored field devices received from WIUs.

If a train does not receive the Office Segment Poll Message within a certain timeout period, the information on mandatory directives and track data becomes outdated. For this reason, after a pre-determined elapsed time since the last Office Segment Poll message was successfully received, the locomotive onboard determines that it can no longer rely on that information. The onboard then prompts the crew with a request to acknowledge that it will disengage from PTC. If the crew does not respond within a certain time, the locomotive onboard will enforce the train to stop. It is assumed for this study that the crew acknowledges the request; i.e., the locomotive onboard disengages in this situation. Office Segment Poll messages are sent periodically every 3 minutes and the locomotive onboard will disengage if three consecutive messages are missed. In a worst-case scenario, if a coverage gap coincides with the location where the next Office Segment Poll is sent and persists for more than 6 minutes, the locomotive onboard will miss three consecutive messages, as illustrated in Figure 60. As a result, the PTC system will not be protecting train operation if there is a loss of Office-to-Locomotive communications for a duration of between 6 and 9 minutes. This study assumes 6 minutes as the threshold for assuming that the locomotive onboard is disengaged.

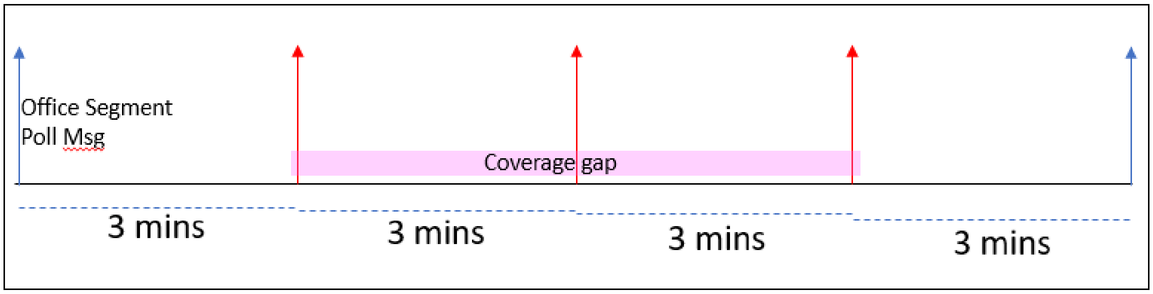


Figure 60. Coverage Gap Threshold for Office Segment Poll Messages

WSRS messages only impact PTC operation in territories where trains are dependent on WSRS to receive WSMs. The status of the monitored wayside signaling devices are constantly updated to WSRS servers. In territories where WIUs do not have their own 220-MHz radios, or where trains cannot reliably receive WSMs directly from WIU radios, the WSRS server relays WSMs to trains; thus, trains operating in these territories depend on the Office-to-Locomotive link to receive WSMs. In territories where WIUs have their own 220-MHz radios, the WIUs communicate the WSMs directly to the trains without depending on the Office-to-Locomotive link. The PTC onboard system is currently designed to assume the most restrictive state of a wayside device if it does not receive the status of that device for more than four 220-MHz radio superframe cycles, which equates to 16 seconds. Therefore, in territories where WIUs rely on

WSRS for communication of WSMs, a loss of Office-to-Locomotive communications for a duration of 16 seconds when approaching a WIU will cause trains to stop and negatively impact operations.

Locomotives can communicate with the back office through multiple communication paths, including Wi-Fi, cellular, and 220-MHz radios. Railroads equip their locomotives with all three communication paths. The Wi-Fi infrastructure is typically available only at terminals/yards; thus; the analysis of the availability of the Office-to-Locomotive link in this study included only the cellular and 220-MHz radio communication paths.

Thus, the unavailability of the Office-to-Locomotive link is determined by the probability that both communication paths are simultaneously unavailable at a given moment.

TTCI prepared a methodology to account for these conditions that is comprised of the following steps:

1. Determine the probability of a base station continuous coverage gap greater than 6 minutes.
2. Determine the probability of a cell continuous coverage gap greater than 6 minutes.
3. Determine the probability of cell service being down.
4. Determine the probability of both Steps 1 and 2, OR both Steps 1 and 3.
5. Repeat Steps 1 through 4 for coverage gaps greater than 16 seconds for WSRS territory.

The estimation of base station coverage gap sizes per operational scenario (Step 1 from the list above) was prepared with the results of RF simulations along railroad tracks.

For the estimation of cell service (Step 3), TTCI used an aggregate number provided by the railroads (0.997 availability). For the estimation of cell coverage (Step 2), TTCI was provided with the average cell coverage availability per subdivision by one of the railroads. Because data was provided as an average for the entire subdivision, but not as discrete values along the tracks, TTCI was unable to estimate cell coverage gap sizes. As a result, TTCI applied the availability number as the probability of cell coverage. Cell coverage availability was calculated separately for DUA (0.995) and non-DUA (0.984) areas.

Base Station Communication Path Availability

An analysis of the impact of base station failures was performed for each operational scenario, as redundancy of base station coverage is expected to differ for each operational scenario. Two aspects were included in the analysis:

- The impact on PTC protected time when a train cannot communicate with a base station.
- The level of redundant coverage typically observed in each operational scenario.

As explained, if there is a loss of Office-to-Locomotive communications for more than 6 minutes and an Office Segment Poll message is not received, PTC unprotected time will result. In territories where trains depend on WSRS to obtain the status of WIUs, operations will be impacted if there is a loss of Office-to-Locomotive communications for more than 16 seconds. The minimum size of coverage gap that would impact PTC protection is dependent on the speed of the train; i.e., the slower a train operates, the longer it will remain in a coverage gap. Table 36 shows the coverage gap sizes that would impact PTC operation that are WSRS dependent for various train speeds.

Table 36. Coverage Gap Size Impacting PTC Protection Due to Not Receiving WSM in WSRS Territory, as a Function of Train Speed

Train Speed (mph)	40	30	24.6	20
16-second Gap Size (feet)	939	704	577	469

Table 37 shows the coverage gap sizes that would impact PTC protection as a result of not receiving Office Segment Poll messages.

Table 37. Coverage Gap Size Impacting PTC Protection Due to Not Receiving Office Segment Poll Messages, as a Function of Train Speed

Train Speed (mph)	40	30	24.6	20
6-minute Gap Size (miles)	4.0	3.0	2.5	2.0

The coverage gap resulting from the failure of a base station is dependent on the level of redundancy; i.e., how much coverage can be provided by other base stations in the vicinity of the failed base station. TTCI developed a three-step method to determine the typical coverage gaps caused by single base station failure for each of the operational scenarios:

1. Simulate the failure of one base station at a time within a defined area (such as a DUA or a single subdivision) using an RF simulation tool (Planet™), which generates a list of points along the track that are below coverage requirements (coverage gap results).
2. Export coverage gap results to a Microsoft Excel file and visualize in Google Earth™ mapping service to estimate the size of the coverage gap.
3. Process coverage gap sizes and tabulate for the area being analyzed.

Figures 3 and 4 provide a visualization of the coverage gap estimation process.

E

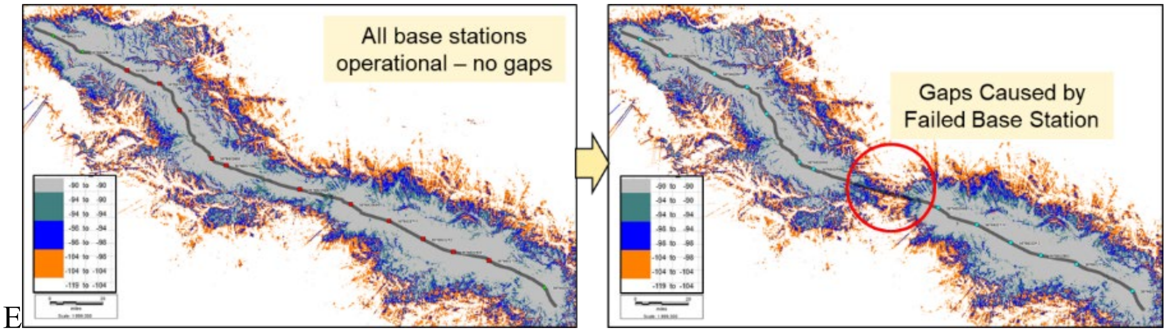


Figure 61. Illustration of Coverage Gaps Resulting from the Failure of a Base Station along the Tracks of a Railroad Subdivision

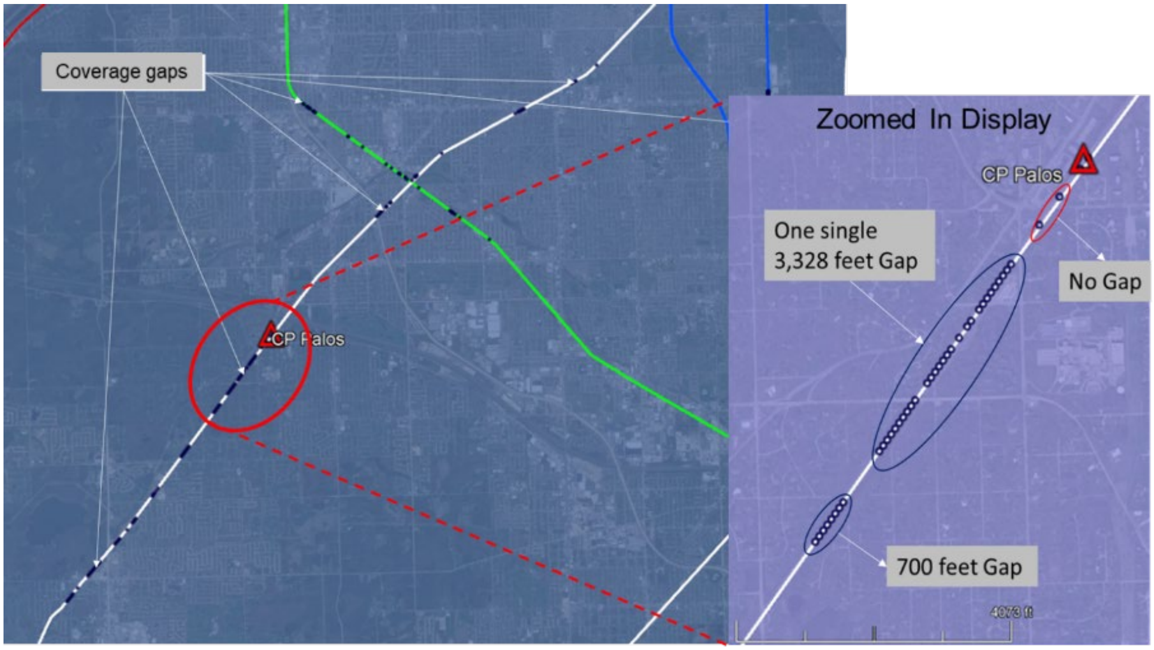


Figure 62. Illustration of Coverage Gap Size Estimation, Using Google Earth

TTCI executed the above method for all operational scenarios using selected reference territories agreed to by the participating railroads. The selected reference territories include subdivisions from BNSF, CSX and UP for the signaled single-, double- and triple-track and dark territory scenarios. For the DUA operational scenario, it includes subdivisions for all railroads operating in the Chicago and Dallas-Fort Worth DUAs. Note that for the DUA operational scenario, coverage provided by foreign base stations (i.e., base stations belonging to a railroad other than the railroad that owns the tracks where coverage is being analyzed) was considered. For all other operational scenarios, coverage provided by non-U.S. base stations was not considered.

TTCI used results of PTC RF network designs studies developed for DUAs [2] and for the Northeast corridor [5] to calculate the coverage gaps in case of base station failure. Table 38 shows the average gap sizes if one base station failed for each operational scenario assuming an average normal train speed of 24.6 mph and average reduced speed of 20.0 mph (and assuming no other communications path was available). The two rightmost columns in Table 38 show the estimated gap sizes for each operational scenario due to base station failure. The Non-WIU Communication (WSRS Dependent) column relates to the impact caused by not receiving WSMs from the WSRS server (through a base station) and this would affect territories where there is exclusive dependency on receiving WSMs from WSRS servers. The PTC Disengagement (No BOS Comms) column relates to the impact caused by outdated mandatory directives and track data information, which affects all territories. Typically, railroads configure their tracks with a large predominance of WIU configuration on their tracks – either WIUs equipped with radios (i.e., not exclusively depending on WSRS) or not (i.e., exclusive WSRS dependency).

Table 38. Average Gap Sizes Resulting from Base Station Failure for Each Operational Scenario

Operation Scenario	Reference					Average Gap Length (miles)	
	MTA	Territory /Subdivision	RR	Route Miles	# of Base Stations	Non-WIU Communication (WSRS Dependent)	PTC Disengagement (No BOS Comms)
DUA	Chicago	Chicago DUA	ALL	1,157	38	**0.62**	**0.04**
	DFW	DFW DUA	ALL	435	26		
Triple-Track	Kansas City	Kearney	UP	140	7	**2.14**	**0.00**
Double-Track	Chicago	Erie	CSX	90	8	**4.47**	**0.87**
	Chicago	Mendota	BNSF	125	5		
Single-Track	Chicago	Joliet	UP	116	7	**9.33**	**3.15**
	DFW	Plainville – Slaton	BNSF	145	7		
	DFW	Wichita	BNSF	210	10		
	Charlotte	Monroe	CSX	141	8		
Dark Territory	New York	St. Lawrence	CSX	137	7	**3.41**	**10.73**
	Wichita	Enid	UP	85	3		

The average gap sizes calculated for each operational scenario were included in the estimation of the availability of the Office-to-Locomotive link in conjunction with the probability that a train reaches a base station that is failed at a given time, and the probability that there is not cell service or coverage.

Appendix F: Detailed PTCIE Train Delay Results

Tables 39 through 50 show the results of train delay per PTCIE. The results were calculated at 50 percent TUL and do not include operational disruption events.

Table 39. En route Onboard Software Recoverable Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Enroute Onboard Software Recoverable			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.14726	N/A	N/A	0.16888
Single Track	2.87053	3.17021	2.98766	2.82026
Double Track	2.92683	3.24328	3.07916	2.66021
Triple Track	0.11287	0.10272	0.09287	0.10263
Dense Urban Area	1.71198	1.68643	1.67816	1.51531

Table 40. Back Office Downtime Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Back Office Downtime			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.00005	N/A	N/A	0.00006
Single Track	0.00009	0.00003	0.00007	0.00013
Double Track	0.00003	0.00002	0.00003	0.00004
Triple Track	0.00003	0.00002	0.00002	0.00004
Dense Urban Area	0.00008	0.00012	0.00014	0.00014

Table 41. PTC Wayside Failure at CP Train Delay per Operational Scenario and Train Control Method

Operational Scenario	PTC Wayside Hardware Failure at CP			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	N/A	N/A	N/A	N/A
Single Track	0.00309	0.00291	0.00246	0.00291
Double Track	0.00286	0.00312	0.00229	0.00296
Triple Track	0.00215	0.00205	0.00173	0.00198
Dense Urban Area	0.00421	0.00446	0.00377	0.00427

Table 42. PTC Wayside Failure at IS Train Delay per Operational Scenario and Train Control Method

Operational Scenario	PTC Wayside Hardware Failure at IS			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	N/A	N/A	N/A	N/A
Single Track	0.00276	0.00302	0.00790	0.00327
Double Track	0.00312	0.00437	0.00777	0.00395
Triple Track	0.00120	0.00090	0.00131	0.00120
Dense Urban Area	0.00066	0.00070	0.00094	0.00066

Table 43. PTC Wayside Failure at Controlled Switch Train Delay per Operational Scenario and Train Control Method

Operational Scenario	PTC Wayside Hardware Failure at Controlled Switches			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.02700	N/A	N/A	0.02700
Single Track	N/A	N/A	N/A	N/A
Double Track	N/A	N/A	N/A	N/A
Triple Track	N/A	N/A	N/A	N/A
Dense Urban Area	N/A	N/A	N/A	N/A

Table 44. En route Onboard Hardware Non-Recoverable Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Enroute Onboard Hardware Non-Recoverable			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.00495	N/A	N/A	0.00499
Single Track	0.03883	0.03969	0.03948	0.04472
Double Track	0.03481	0.04372	0.03855	0.03068
Triple Track	0.00109	0.00101	0.00093	0.00124
Dense Urban Area	0.00698	0.00993	0.01109	0.00707

Table 45. Sync Error Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Sync Error			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.00852	N/A	N/A	0.00772
Single Track	0.02035	0.03016	0.07000	0.04998
Double Track	0.01959	0.01954	0.00976	0.02914
Triple Track	0.00059	0.00118	0.00177	0.00353
Dense Urban Area	0.03537	0.02323	0.03370	0.04834

Table 46. BOS-Loco Link Train Delay per Operational Scenario and Train Control Method

Operational Scenario	BOS-Loco Link			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.00001	N/A	N/A	0.00001
Single Track	0.00003	0.00003	0.00011	0.00009
Double Track	0.00000	0.00000	0.00000	0.00000
Triple Track	0.00000	0.00000	0.00000	0.00000
Dense Urban Area	0.00000	0.00000	0.00000	0.00000

Table 47. En route Operator Error – Speed Enforcement Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Enroute Operator Error - Speed Enforcement			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.00262	N/A	N/A	0.00283
Single Track	0.04785	0.05066	0.03696	0.04701
Double Track	0.02962	0.04267	0.03608	0.04895
Triple Track	0.00139	0.00139	0.00139	0.00277
Dense Urban Area	0.01980	0.02146	0.02076	0.01985

Table 48. En route Operator Error – Other Enforcement Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Enroute Operator Error - Other Enforcement			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.02185	N/A	N/A	0.02357
Single Track	0.39862	0.42203	0.30787	0.39164
Double Track	0.24677	0.35548	0.30060	0.40780
Triple Track	0.01158	0.01155	0.01154	0.02307
Dense Urban Area	0.16496	0.17875	0.17293	0.16534

Table 49. Initialization Delay Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Initialization Delay			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.00566	N/A	N/A	0.00560
Single Track	0.08114	0.08018	0.07976	0.07972
Double Track	0.07813	0.07792	0.07787	0.07747
Triple Track	0.00472	0.00470	0.00470	0.00470
Dense Urban Area	0.04701	0.04631	0.04480	0.04283

Table 50. Initialization Onboard Hardware Failure Train Delay per Operational Scenario and Train Control Method

Operational Scenario	Initialization Onboard Hardware Failure			
	Total Train Delay (Minutes/100,000 Train-miles)			
	Overlay PTC	EO-PTC	QMB	FMB
Dark Territory	0.00000	N/A	N/A	0.00156
Single Track	0.02261	0.02234	0.02222	0.02221
Double Track	0.02177	0.02171	0.02170	0.02158
Triple Track	0.00131	0.00131	0.00131	0.00131
Dense Urban Area	0.01310	0.01290	0.01248	0.01193

Appendix G: PTC Requirements for Railroad Network Simulation

Background and Scope

This document contains the list of requirements that a Railroad Network Simulator ("the Simulator") must satisfy to provide the features needed for the Higher Reliability and Capacity Train Control (HRCTC) project.

It is assumed that the Simulator already implements functions to simulate a railroad network model including train operations in signaled and non-signaled territories.

The requirements herein described aim to provide functions in the Simulator to analyze potential impacts and/or benefits with the implementation of PTC and potential new methods of train control in a railroad network. The Simulator shall provide functions to simulate PTC-related failure events (e.g., failures in PTC components or human errors impacting train operation) and their impacts on train operations, as well as functions to quantify benefits (e.g., the ability to not necessarily reduce speed at approach signals on PTC-equipped trains, or the implementation of a moving block concept).

The requirements are divided in three groups, per planned development phases. The first phase includes the requirements needed to simulate PTC as it is being currently deployed by U.S. railroads (PTC Overlay). The second phase includes the requirements needed to simulate currently envisioned technologies/methods that could be applied in addition/extension to PTC; specifically moving block methods. A third development phase may be required if additional features are needed to address some of the analysis required and/or due to new methodologies/technologies that can be identified as the HRCTC project evolves.

Each section of this document generally contains two parts: narrative text and explicit requirements. The narrative text includes background information, goals, and other supplemental information provided to clarify the requirements. The explicit requirements, each containing the word "shall," follow in a numbered or lettered list beneath the narrative text.

Concepts and Terminology

For purposes of this document, the following concepts and terminology will be used:

- Control Points and Control Blocks:
    - In a Manual Block System (MBS), such as Track Warrant Control (TWC), a control point is any point identified in the dispatching system where one train can clear the main track to allow another train to pass. It may be at a siding or a junction. A control block extends between two successive control points.
    - In Centralized Traffic Control (CTC) systems (including PTC overlay systems), a control point is any signal that can be "controlled" by the train dispatcher; that is, a dispatcher may request a permissive signal or may command the signal to a Stop indication. The vast majority of controlled signals are at power-operated switch locations, but a controlled signal may also be placed at a location where a dispatcher may need to hold a train. All controlled signals are absolute signals and a train may not pass one that is displaying a Stop indication without dispatcher authority. A control block extends between two successive controlled signals governing movement in the same direction.

  - Note that signals governing entry to an automatic interlocking (railroad crossing at grade) are also absolute signals, requiring specialized procedures to pass in the event of a signal system failure. These are not considered as controlled signals for purposes of defining a control block.
- Signal Block: Extends between two successive signals governing movement in the same direction.

Phase 1 Functional Requirements – PTC Overlay Operation

The list of requirements for this phase is divided into six groups:

1. Overall system configuration
2. Train braking in PTC operation
3. PTC response to signal aspect upgrades
4. PTC-related events that impact train operations.
5. Rules that govern operations for trains under PTC failure (fallback operation).
6. Configurable signal rules

The requirements under each group are listed in the following subsections.

Overall System Configuration

The following requirements describe overall PTC configuration parameters for the Simulator.

For trains to operate under PTC control, both the track and trains must be configured for PTC operation. Thus, the Simulator shall provide features to allow the user to set tracks and trains in such condition.

The Simulator shall allow the user to display and select the sets of PTC configurations that will be active for a simulation run.

Table 51 lists the requirements to be satisfied by the system under this group.

Table 51. Requirements for Overall System Configuration

Req. ID	Req. Description
SC01	The Simulator shall allow the user to toggle ON/OFF tracks for PTC Mode operation at different levels: 1. To the entire model 2. To designated subdivisions within the network and/or to designated segments (between control points or model nodes) within one or more subdivisions
SC02	The Simulator shall allow the user to toggle ON/OFF trains to operate in PTC Control at different levels: 1. To a specific train 2. To a class of trains (such as passenger, freight, etc.) 3. To a subgroup of trains 4. To all trains in the entire model
SC03	The Simulator shall allow the user to toggle ON/OFF an entire model to operate in PTC Mode. When turned ON, The Simulator shall activate PTC functions for the tracks set to PTC Mode ON and for trains set to PTC Control ON.
SC04	The Simulator shall allow the user to display and select the sets of PTC configuration parameters that will be active in a simulation run. The sets of PTC configuration parameters: 1. Train braking in PTC operation 2. PTC response to signal upgrades 3. Individual train operation impact events 4. WIU failure events 5. Script mode events 6. Fallback operation.
SC05	The Simulator shall allow the user to configure maximum train speeds (in mph) to be used under certain operational scenarios: • Restricted Speed (SC05_RS). Default value = 20 mph • Medium Speed (SC05_MS). Default value = 30 mph
SC06	1. The Simulator shall allow the user to indicate which method of PTC operation should be applied for the tracks set for PTC Mode operation: 2. PTC Overlay (default): trains are simulated per Phase1 requirements. 3. QMB: trains are simulated per Phase1 and Phase 2 requirements . 4. FMB: trains are simulated per Phase1 and Phase 2 requirements..
SC07	The Simulator shall allow the user to indicate the method of PTC operation (SC06) per the following: 1. For an entire subdivision 2. For a group of subdivisions 3. For the entire model

Requirements for Train Braking in PTC Operation

This group includes the requirements for the simulation of train braking behavior in PTC operation.

In concept, there are three types of train braking curves the Simulator should implement:

1. **Full-Service Application**: How train actually brakes when a PTC enforcement or critical failure occurs.
2. **Normal Service Application:** The manner in which the engineer brakes at events that are not affected by PTC, such as crew change points or station stops. Trains not operating under PTC will also use Normal Service Application.
3. **PTC Braking Curve:** How the OBC will calculate the braking curve at events that are monitored by PTC, such as enforceable stops (stop signals and roadway worker work limits) and enforceable speed reductions (civil speed reductions, temporary speed reductions and turnout speeds). Currently, this is more conservative than normal service braking; however, ways to make the prediction of enforcement braking rate closer to actual enforcement braking rate (full-service application) are being investigated/developed and will be likely implemented as PTC deployment evolves.

Figure 63 illustrates those three types of braking curves.

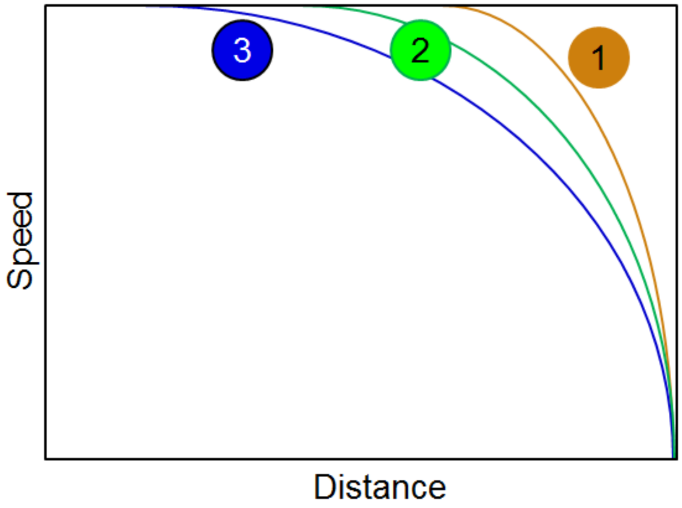


Figure 63. Illustration of the Three Conceptual Types of Braking Curves

Prior to enforcement, a count-down of time to enforcement is displayed to the train engineer. The start of reduction (SoR) in train speed under train engineer control occurs several seconds before the countdown reaches zero in the OBC display to prevent unwanted initiation of enforcement braking. Typically, the faster the train is operating, the earlier the train engineer will start braking the train to ensure that the PTC system detects that the train is under control. Figure 64 illustrates the effect, showing the train engineer's reaction in distance.

It is also known that the SoR is not only dependent on the train speed but also on the train type. For example, a typical SoR of a freight train travelling at 60 mph would be around 20 to 30 seconds, while for a passenger train it would be typically lower (5 to 10 seconds). A freight train travelling at 20 mph would also typically have a SoR lower than when the same train is at 60 mph. For that reason, the Simulator will take a typical response time at a certain speed (for example, 60 mph) and interpolate it proportionally to the PTC Braking Curve for other train speeds.

For practical purposes, the engineer braking with PTC will become the PTC Braking Curve (calculated by the OBC) plus the reaction time of the train engineer to TTE.

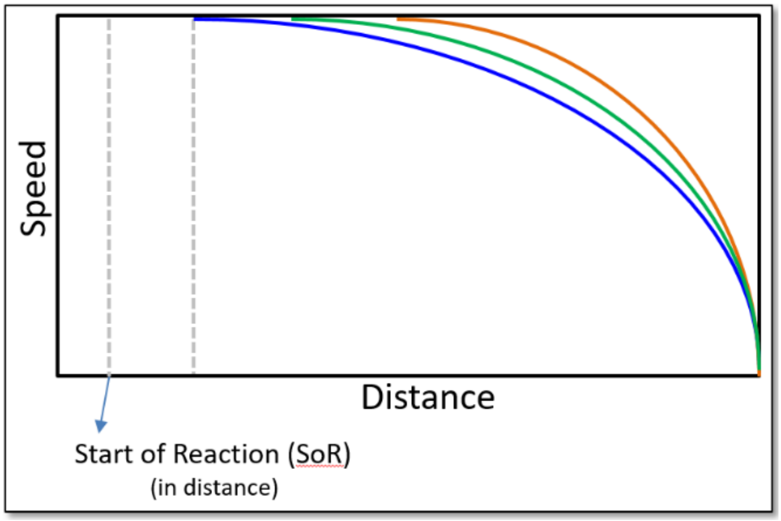


Figure 64. Illustration of the Reaction of the Train Engineer to the Time to Enforcement Indication in the OBC

Table 52 lists the requirements to be satisfied by the Simulator, based on these conceptual braking curves above described.

Table 52. Requirements for Train Braking in PTC Operation

Req. ID	Req. Description
TB01	For trains set to PTC Control ON and operating on tracks with PTC Mode ON, the Simulator shall simulate train braking operation based on three braking rates in mph/sec: 1) Full-Service Application; 2) Normal Service Application; and 3) Engineer Braking with PTC. 1. **Full-Service Application** rate (TB01_FSA) shall be used for PTC system onboard failures to determine where the train will stop as a result of the failure. 2. **Normal Service Application** rate (TB01_NSA) shall be used for train stops when the train engineer is not influenced by the PTC onboard system, such as stops at yards or other work points to perform work; crew change points; or station stops (unless the braking curve due to a stop signal beyond the station stop is more restrictive). 3. **PTC Braking Curve** rate (TB01_PBC) shall be used for braking when approaching stop signals, signal speed reductions, civil speed reductions, temporary speed reductions (Form A), work limits in effect (Form B), and entering non-controlled track (Restricted Speed). – The Simulator shall also account for the Start of Reaction time of the train engineer, (TB03_SOR), to start the braking application. – **Exception**: When the braking rate of the PTC Braking Curve is greater than the braking rate of the Normal Service Application for any class of train, the Simulator shall use the Normal Service Application braking rate.
TB02	The Simulator shall allow the user to set train deceleration values in mph/sec. for the three different braking rates defined in TB01: • For a specific train • For a class of trains (such as passenger, freight, etc.) • For a subgroup of trains • For all trains in the entire model
TB03	The Simulator shall allow the user to set the Start of Reaction time (TB03_SOR), in seconds for a given speed (in mph): • For a specific train • For a class of trains (such as passenger, freight, etc.) • For all trains in the entire model
TB04	The Simulator shall allow the user to display the list of existing train braking configuration parameters.
TB05	The Simulator shall allow the user to select an entry from the list and perform an action, per the following: 1. ACTIVATE – The Simulator shall make the selected entry Active. 2. EDIT – The Simulator shall open the selected entry and allow the user to modify its braking parameters (TB01 to TB03).

Req. ID	Req. Description
	3. NEW – The Simulator shall add a new entry in the list and: a. The Simulator shall allow the user to give a name to the entry. b. The Simulator shall allow its braking parameters (TB01 to TB03) to be modified by the user. 4. DELETE – The Simulator shall delete the selected entry, after confirmation of the action from the user. 5. RENAME – The Simulator shall allow the user to change the name of the selected entry. The name of an entry in the list shall be alphanumeric with up to 40 characters.
TB06	The Simulator shall allow the user to save an entry that is being edited as a new entry in the list.

Requirements for PTC Response to Signal Aspect Upgrades

Each signal aspect/indication identifies the requirements at this signal and what is to be expected at the next signal. A signal indication upgrade occurs when a condition changes ahead to permit the signal to convey an indication that is less restrictive than before the condition changed. When a train is operating without PTC control, the train engineer is typically driven by the last signal aspect observed; the operational target cannot be changed until the next aspect can be seen. With PTC control, signal aspects are conveyed to the train engineer through the OBC display when they actually happen, which many times will be at a location ahead of the location where the next aspect would become visible to the train engineer. Generally, in these cases the train engineer is taking actions to slow the train to a slower speed or to a stop. On becoming aware of a signal indication upgrade, the train engineer may continue at the current train speed to the upgraded signal and then handle the train at that signal in accordance with the new indication.

This group of requirements describes how the Simulator must react when a signal ahead of the train is upgraded when the train is under PTC Control and operating on tracks configured with PTC Mode ON.

Table 53 lists the requirements to be satisfied by the Simulator under this group.

Table 53. Requirements for PTC Response to Signal Aspect Upgrades

Req. ID	Req. Description
RU01	The Simulator shall allow the user to turn the Signal Aspect Upgrades feature ON or OFF. When turned OFF, Signal Aspect Upgrades features (RU02 to RU05) shall not be in effect.
RU02	For trains set to PTC Control ON and operating on tracks with PTC Mode ON, when the signal aspect/indication in advance of a train is upgraded and the train has been operating with a Stop and Proceed signal authority or a Restricted Proceed signal authority, or a Restricting signal authority, the Simulator shall continue simulating the train to the next signal in advance of the train at Restricted Speed (SC05-RS).
RU03	For trains set to PTC Control ON and operating on tracks with PTC Mode ON, when the signal aspect/indication in advance of a train is upgraded and the train is operating under a restrictive signal authority other than those in RU01 towards that signal, the Simulator shall simulate the resumption of speed per the upgraded signal aspect/indication four seconds after the signal aspect upgrade.
RU04	The Simulator shall allow the user to define at what sight distance (in feet) the train engineer will be able to see the next signal, per the following: _For the entire model (RU04_SDM) – default: 500 feet _For a subdivision (RU04_SDS) – default: empty _For an individual signal (RU04_SDI) – default: empty Configuration values defined for subdivision supersedes values informed for the entire model. Configuration values defined for individual signals supersedes values informed for subdivision and entire model.
RU05	For trains set to PTC Control OFF, when the signal aspect/indication in advance of a train is upgraded and the train is operating under a restrictive signal authority other than those in RU01 towards that signal, the Simulator shall simulate the resumption of speed per the upgraded signal aspect of the next signal when the train is within sight distant from the next signal, as specified in RU04.
RU06	The Simulator shall allow the user to display the list of existing Response to Signal Aspect Upgrade Configuration Parameters entries.
RU07	The Simulator shall allow the user to select an entry from the list and perform an action, per the following: 1. ACTIVATE – The Simulator shall make the selected entry Active. 2. EDIT – The Simulator shall open the selected entry and allow the user to modify its parameters (RU01 to RU05). 3. NEW – The Simulator shall add a new entry in the list, and: a. The Simulator shall allow the user to give a name to the entry b. The Simulator shall make its parameters (RU01 to RU05) enabled to be modified by the user.

Req. ID	Req. Description
	4. DELETE – The Simulator shall remove the selected entry, after confirmation of the action from the user. 5. RENAME – The Simulator shall allow the user to change the name of the selected entry. The name of an entry in the list shall be alphanumeric with up to 40 characters.
RU08	The Simulator shall allow the user to save an entry that is being edited as a new entry in the list.

PTC-related Events that Impact Train Operations

There are several PTC-related events that can impact train operations. Table 54 lists the potential events currently identified and their impact in train operation.

Table 54. List of PTC-Related Events that Impact Train Operations

No.	Category	PTC Operation Impact Event	Impact in train operation
1	**Train Initialization**	Issues with system (various potential sources) causing train delay at departure time.	Causes delay to train departure. Train subsequently departs with normal PTC operation.
2		Human error at system configuration/initialization causing train delay at departure time.	Causes delay to train departure. Train subsequently departs with normal PTC operation.
3		Issues (various potential sources, including human error), causing PTC disengagement (missed opportunity).	Causes train to operate disengaged per PTC Overlay Fallback mode until destination.
4	**Onboard Event En route**	Onboard failure causing enforcement (non-recoverable).	Causes train to stop, cut-out brakes, and resume operation per PTC Overlay Fallback mode.
5		Onboard failure causing enforcement (recoverable).	Causes train to stop, resume normal PTC operation after delay.
6		SW Defect causing enforcement (recoverable).	Causes train to stop, resume normal PTC operation after delay.
7		State change from "Active to Disengaged" (non-recoverable)	Causes train to slow to fallback speed, operate per PTC Overlay Fallback mode until destination.
8		State change from "Active to Disengaged" (recoverable)	Causes train to slow to fallback speed, operate per PTC Overlay Fallback mode until recovery.
9	**Human Error En route**	Non-confirmation of switch position under WIU failure in non-signaled territory causing train enforcement.	Causes train to stop if crew does not confirm switch position in time. Train resumes operating at normal PTC operation after delay.
10		Human error at system configuration/initialization causing train enforcement.	Causes train to stop, resume operating at normal PTC operation after delay.
11		Human error during operation causing train enforcement.	Causes train to stop, resume operating at normal PTC operation after delay.

No.	Category	PTC Operation Impact Event	Impact in train operation
12	**WIU Non-communicating**	WIU Msg Status not received from intermediate signal.	Causes a Stop target to be applied at the intermediate signal. If the signal indication is Restricting, the Stop target is lifted when the train speed is at or below the maximum speed for Restricted Speed and a Restricted Speed limit is applied for the next signal block. If the signal indication is Stop and Proceed, the Restricted Speed limit is applied after the train has stopped.
13		WIU Msg Status not received from absolute signal.	Causes train to slow down per stop target at signal, stop to obtain dispatch authority and operate at Restricted Speed through next signal block then resume normal PTC operation.
14		WIU Msg Status not received from monitored switch in non-signaled territory.	Causes train to slow down per stop target at inoperative WIU, operate at normal permitted speeds after crew confirms switch position.
15	**Office Fault**	Synchronization error of train with Office	Causes the train to slow to fallback speed, operate per PTC Overlay Fallback mode until recovery.
16		Office services are down.	Causes all trains registered to the Office Servers to slow to fallback speed, operate per PTC Overlay Fallback mode until recovery.
17	**Base Station Non-communicating**	Base station failure causing trains to disengage PTC (WIUs have own radio).	When one of the two conditions below (whichever happens first) is reached, train will resume normal PTC operation as indicated: 1) BOS Heartbeat timeout (558 seconds). Train slows to fallback speed, operate per PTC Overlay Fallback mode until coverage is regained. 2) Train reaches end of current movement authority and needs a new TW. Train will stop, resume per PTC Overlay Fallback mode after obtaining new movement authority until coverage is regained.

No.	Category	PTC Operation Impact Event	Impact in train operation
18		Base station failure causing WIU messages not to be transmitted (WIUs do not have own radio).	When one of the three conditions below (whichever happens first) is reached, train will resume operation as indicated: 1) BOS Heartbeat timeout (558 seconds). Train slows to fallback speed, operate per PTC Overlay Fallback mode until coverage is regained. 2) Train reaches end of current movement authority and needs a new TW. Train will stop, resume per PTC Overlay Fallback mode until coverage is regained. 3) Train needs to communicate with a WIU. Train will operate as per WIU non-communicating (events 12, 13, and 14.)
19	**Comms Backbone Failure**	Trunk communication line controlling multiple base stations fails.	Causes trains under the coverage of the failed base stations to be affected according to what is described in the Base Station non-communicating condition (events 17 and 18), depending on the configuration of the bases.

The impact in train operation varies depending on the type of event, as indicated in Table 54 (Impact in Train Operation column). Some events cause just the disengagement of PTC or a train delay while others will cause a train to stop. Some events may be recoverable (i.e., return to normal PTC operation immediately after the event occurs or after some time), or not (i.e., train will operate under PTC Fallback mode until destination). The system shall provide the user the ability to configure each one of the events in Table 54 with their own configurable parameters.

Note that for Phase 1 development, only event types 1 to 15 need to be included. Events 16 to 19 may be included in Phase 3, if needed.

The PTC Operation Impact events are divided in the list of requirements into two groups:

1. **Individual Train Operation Impact Events** – These are events that are specific to one individual train, and thus affect directly that train only (such as events 1 to 11 and 15).
2. **WIU Failure Events** – These are related to WIU failures (such as events 12, 13, and 14). When a WIU fails, all PTC-controlled trains that operate across that failed WIU will be affected until it is repaired and restored to normal operation; i.e., potentially this type of events can affect multiple trains.

PTC Operation Impact events will also have to be triggered in the Simulator per the following criteria:

1. **Script Mode:** PTC-related failure events set to specific train/trains; each at a specific location; each at a specific time. There can be more than one scripted event per simulation run.

2. **Random Mode:** PTC-related failure events are triggered based on a user-defined probability.

Requirements for Individual Train Operation Impact Events

Table 55 lists the requirements to be satisfied by the system for each of the events that impact individual trains (such as events 1 to 11 and 15, from Table 54).

Table 55. Requirements for Individual Train Operation Impact Events

Req. ID	Req. Description
IO01	The Simulator shall allow the user to view the list of existing Individual Train Operation Impact Configuration Parameters.
IO02	The Simulator shall allow the user to select an entry from the list of Individual Train Operation Impact Configuration and perform an action, per the following: 1. ACTIVATE – The Simulator shall make the selected entry Active. 2. EDIT – The Simulator shall open the selected entry and allow the user to modify its parameters (IO04 to IO21). 3. NEW – The Simulator shall add a new entry in the list and: a. The Simulator shall allow the user to give a name to the list. b. The Simulator shall make its parameters (IO04 to IO21) enabled to be modified by the user. 4. DELETE – The Simulator shall remove the active entry, after confirmation of the action from the user. 5. RENAME – The Simulator shall allow the user to change the name of the selected entry. The name of an entry in the list shall be alphanumeric with up to 40 characters.
IO03	The Simulator shall allow the user save an entry that is being edited as a new entry in the list.
IO04	The Simulator shall allow the user to ADD, EDIT or DELETE events from the active Individual Train Event Configuration Entry. Each entry in the list will have multiple fields to be configured, as described in the next requirements.
IO05	The Simulator shall allow the user to enter/edit the name of the event type. The field shall be alphanumeric with up to 60 characters.

Req. ID	Req. Description
IO06	The Simulator shall allow the user to select individually for each Individual Train Operation Impact event, which type of trigger should be used for the event, either “SCRIPT,” “RANDOM,” or “NONE” mode: • SCRIPT – The Simulator shall trigger the event per the triggering commands included in the script. • RANDOM – The Simulator shall trigger the event per the probability number defined for the event (per IO08_PRO). • NONE – The Simulator shall not trigger the event during simulation.
IO07	The Simulator shall trigger events only to affect trains configured with PTC Control ON and operating on tracks that are configured with PTC Mode ON.
IO08	The Simulator shall allow the user to set a probability value to trigger each failure event to occur based on one or more of the following conditions: • Simulation clock time since the beginning of the simulation (IO08_SCT) • After total train-miles of the simulation reaches a value provided by the user (IO08_TTM). • After total train-hours of the simulation reaches a value provided by the user (IO08_TSH).
IO09	For failure events that will be triggered randomly (per IO06), when a trigger event is reached, the Simulator shall randomly select an active train configured with PTC Control ON and apply the triggered failure to that train. For train-mile and train-hour triggers, when a failure is applied to a train, the respective counters shall be reset, ready for a new trigger event.
IO10	The Simulator shall allow the user to set under which train operation status the event should occur: • **Departure**: The Simulator shall trigger the event at departure time (before train departs from origin). • **En route**: The Simulator shall trigger the event after train departs from its origin.
IO11	The Simulator shall allow the user to set whether the event causes enforcement to the train or not (IO11-ENF).
IO12	The Simulator shall allow the user to set whether train enforcement is to happen immediately when the event occurs or at the next speed restriction target (IO12-BRM).
IO13	If the event is set to cause enforcement to the train (per IO11-ENF) and it causes an immediate train brake application (per IO12-BRM), when it occurs the Simulator shall immediately apply Full-service Application Brakes, (per TB01_FSA).

Req. ID	Req. Description
IO14	If the event is set to cause enforcement to the train (per IO11-ENF) and it causes the train brake application at the next speed restriction target (per IO12-BRM), the Simulator shall apply Full Service Application (per TB01_FSA) starting the braking application at the point where the braking curve would start for the next target speed reduction. The next target speed reduction can be determined by any of the following: • Signal aspects • Temporary Speed Restriction/Form A • MOW Work Limits/Form B • Civil Speed Reduction • Switch speed
IO15	The Simulator shall allow the user to set whether the event causes an additional delay to the train or not (IO15-TDE).
IO16	If the event causes a delay to the train (per IO15-TDE), the Simulator shall allow the user to configure the minimum and maximum time (in hours and minutes) that the train will be delayed until it can resume operations.
IO17	If an event is set to cause a delay to a train when it occurs (per IO15-TDE), the Simulator shall restore operations for the train after a randomly generated time delay using a uniform distribution between a defined minimum and maximum delay (IO16-MDE).
IO18	The Simulator shall allow the user to set whether the event causes the train to disengage from PTC or not (IO18-DIS).
IO19	If the event causes the train to disengage from PTC (per IO18-DIS), the Simulator shall allow the user to set whether the train will restore to Normal PTC operation or not (IO19-RNO).
IO20	If the train is to restore to Normal PTC Operation after it resumes operation (per IO19-RNO), the Simulator shall allow the user to configure the minimum and maximum time (in hours and minutes) that the train will operate with PTC disengaged (IO20-MDI).
IO21	If an event is set to cause a train to restore to Normal PTC Operation (per IO19-RNO), the Simulator shall restore normal PTC operations for the train after a randomly generated time delay using a uniform distribution between a defined minimum and maximum time to restore to Normal PTC Operation (per IO20-MDI). If the minimum and maximum times are set to 00:00 (per IO20-MDI), the Simulator shall restore Normal PTC Operation immediately after the train resumes its operation.
IO22	If an event causes a train to disengage from PTC (per IO18-DIS), the Simulator shall model that train to function per the PTC Fallback Operation while the train has PTC disengaged.

Req. ID	**Req. Description**
IO23	The Simulator shall record all the impact events that occurred during a simulation run, including: • ID of the train impacted by the event. • Event type • Timestamp when event occurred. • Location the train was when event occurred. • Train stop time duration, if train was enforced. • Timestamp when train was restored to normal PTC operation, if train was able to restore.
IO24	The Simulator shall allow the user to retrieve and visualize the impact events that occurred during a simulation run.
IO25	The Simulator shall allow the user to export the impact events to an external file in CSV format.

Table 56 illustrates a potential design for an interface where the user would configure parameters for Individual Train Operation Impact events.

Table 56. Potential Interface Design/Layout for Individual Train Operation Impact Event

Event Name	**Trigger Mode (Random/Script/NONE)**	**Probability of Occurrence (%)**	**Train Operation Status (Departure/ Enroute)**	Causes Enforcement to Train?	Causes Delay to Train?	Minumum Delay (hh:mm)	Maximum Delay (hh:mm)	Causes Train to Disengage PTC?	Restores to Normal PTC Operation?	Minimum Time to Restore to Normal PTC Operation (hh:mm)	Maximum Time to Restore to Normal PTC Operation (hh:mm)
Train Departure Delay due to Human error	RAMDON	0.00055	DEP	N	Y	0:20	0:40	N	N	0:00	0:00
Train Departure Delay due to System error	RAMDON	0.00055	DEP	N	Y	0:20	0:40	N	N	0:00	0:00
Train Diesengagement at Departure	RAMDON	0.00055	DEP	N	N	0:00	0:00	Y	N	0:00	0:00
Onboard failure causing enforcement (non-recoverable).	SCRIPT	0.00066	ENR	Y	Y	0:10	0:30	Y	N	0:00	0:00
XXXXXXXXXXXXXXXX	xxx	9.99999	xxx	Y/N	Y/N	hh:mm	hh:mm	Y/N	Y/N	hh:mm	hh:mm
XXXXXXXXXXXXXXXX	xxx	9.99999	xxx	Y/N	Y/N	hh:mm	hh:mm	Y/N	Y/N	hh:mm	hh:mm
XXXXXXXXXXXXXXXX	xxx	9.99999	xxx	Y/N	Y/N	hh:mm	hh:mm	Y/N	Y/N	hh:mm	hh:mm

Requirements for WIU Failure Events

When a WIU fails, trains approaching the location where the WIU is monitoring (Control Point or Intermediate Signal in signaled territory or a Monitored Switch in non-signaled territory), will be impacted (such as events 12, 13, and 14 from Table 54).

For signaled territories, the impact varies depending on whether the component is a Control Point or an Intermediate signal. The requirements describe the difference in the impact. It is assumed that the visual signals are still operational and train engineers will abide to the signal aspects indicated to proceed in Fallback operation mode.

For non-signaled territories, the reaction of the OBC will depend on how the train engineer responds to the system instructions. The following sequence will occur:

1. When a train approaches a WIU in failure, the OBC will ask the train engineer to confirm whether the switch is aligned to the desired position.
2. If the train engineer fails to confirm the position of the switch, the OBC will assume that the train needs to stop before the controlled switch and will calculate the braking curve accordingly. The OBC will enforce the train engineer to operate the train per the braking curve.
3. When the train engineer is able to see the position of the switch and confirm, the OBC will resume the train to normal PTC operation. This assumes that the switch is correctly aligned.
    a. It is the consensus among the Railroad's Advisory Group for this project that train engineers typically can see/confirm the position of the switch when the train is 500 feet from the monitored switch.
    b. If the train engineer cannot see/confirm the position of the switch, the OBC will enforce the train to stop. The train engineer must verify/confirm the status of the switch, inform the system, and proceed with normal PTC operation. This will cause a delay in train operation.

Table 57 lists the requirements to be satisfied by the Simulator for WIU Failure Events.

Table 57. Requirements for WIU Failure Events

Req. ID	Req. Description
MO01	The Simulator shall allow the user to select individually for each type of WIU Failure event which type of trigger the simulation run should use, either "SCRIPT," "RANDOM," or "NONE": • SCRIPT – The Simulator shall trigger the event per the triggering commands included in the script. • RANDOM – The Simulator shall trigger the event per the probability number defined for the event (per MO02-PRE). • NONE – The Simulator shall not trigger the event during simulation.

Req. ID	Req. Description
MO02	The Simulator shall allow the user to set a probability value to trigger each type of WIU failure event based on one or more of the following conditions: • Simulation clock time since the beginning of the simulation (MO02_SCT) • WIU operational hours since the beginning of the simulation (MO02_WOH)
MO03	For the events that will be triggered randomly (per MO01), when a trigger event is reached, the Simulator shall randomly select a WIU and apply the triggered failure to that WIU. For failures triggered by WIU operational hours, when a failure is applied to a WIU, the operational hour counter shall be reset, ready for a new trigger event.
MO04	The Simulator shall allow the user to configure the minimum and maximum time (in hours and minutes) that a WIU will remain in failure condition until it is restored to a normal condition (MO04-MTR), individually for each of the WIU types (Control Point, Intermediate Signal and Monitored Switch).
MO05	The Simulator shall allow the user to configure MO04-MTR per the following: • For the entire model – Configuration shall be applied to all WIU locations. • On a subdivision base – Configuration values will apply to all WIUs in the subdivision. This superimposes values that may have already been assigned for the entire model • Individually for a single WIU component – This superimposes values that may have already been assigned for the entire model and for the subdivision to which the WIU belongs.
MO06	When a WIU failure event is triggered (per MO02) and there is no explicit scripted time to restore the component, the Simulator shall restore the failed WIU to normal condition based on a uniform distribution probability, from a minimum to a maximum duration (per MO04-MTR).
MO07	The Simulator shall allow the user to configure the minimum and maximum time (in hours and minutes) that a train will remain stationary when a train stops due to a WIU Failure event (MO07-TST), separately for Control Point and Monitored Switch WIU types.
MO08	The Simulator shall trigger WIU Failure events only to locations (Control Points, Intermediate Signals and monitored switches) on tracks that are configured with PTC Mode ON.
MO09	When a WIU Failure event occurs to an Intermediate (permissive) Signal (Event type 12), the Simulator shall: • Treat the signal as a Stop and Proceed aspect for the trains approaching that signaling location. • Reduce train speeds using Engineer Braking with PTC braking rate (per TB01).

Req. ID	Req. Description
	• When train reduces to restricted speed (per SC05_RS), the *Simulator* shall allow train to continue to next signal, operating at restricted speed according to signaling conditions ahead.
MO10	When a WIU Failure event occurs at a Control Point (Event type13), the Simulator shall: • Treat the signal as a Stop aspect for the trains approaching that Control Point. • Reduce train speeds using PTC Braking Curve rate (per TB01_PBC) and stop at the Control Point location.
MO11	The Simulator shall allow the user to set whether trains will stop or not when approaching a monitored switch in a non-signaled territory whose WIU is in failure (MO11-MSS).
MO12	The Simulator shall allow the user to define at what sight distance in feet (MO12-SDR) a train will resume normal PTC operations when approaching a monitored switch in a non-signaled territory whose WIU is in failure. Default value shall be 500 feet.
MO13	When a WIU Failure event occurs to a monitored switch in non-signaled territory (event type 14) and a train is approaching this monitored switch, the Simulator shall: 1. Reduce train speed using PTC Braking Curve rate (per TB01_PBC). 2. If it is configured that trains should stop in such condition (per MO11-MSS), the Simulator shall enforce train to stop at the failed signal target; otherwise the Simulator shall resume normal PTC train operation when the train is MO12-SDR feet away from the location of the monitored switch.
MO14	The Simulator shall restore normal PTC operation for a train that stops due to a WIU Failure at Control Points and Monitored Switches after a randomly generated time delay using a uniform distribution between a defined minimum and maximum delay (MO07-TST), obeying the signal aspect displayed. (*This assumes that the signal is displaying a valid aspect, but the WIU is unable to communicate the aspect. As the train will stop short of the signal, it is assumed that the engineer can see the signal aspect and proceed according to the rules.*)
MO15	The Simulator shall allow the user to view the list of existing WIU Failure Events Configuration Parameters.
MO16	The Simulator shall allow the user to select an entry from the list of existing WIU Failure Events Configuration Parameters and perform an action, per the following: 1. ACTIVATE – The Simulator shall make the selected entry Active. 2. EDIT – The Simulator shall open the selected entry and allow the user to modify its parameters (MO01 to MO14). 3. NEW – The Simulator shall add a new entry in the list and: a. The Simulator shall allow the user to give a name to the entry. b. The Simulator shall make its parameters (MO01 to MO14) enabled to be modified by the user.

Req. ID	Req. Description
	4. DELETE – The Simulator shall delete the active entry, after confirmation of the action from the user. 5. RENAME – The Simulator shall allow the user to change the name of the selected entry. The name of an entry in the list shall be alphanumeric with up to 40 characters.
MO17	The Simulator shall allow the user save an entry that is being edited as a new entry in the list.
MO18	The Simulator shall record all the WIU failure events that occurred during a simulation run, including: • ID of the WIU that failed. • Timestamp when event occurred. • Timestamp when WIU was restored to normal operation.
MO19	The Simulator shall allow the user to retrieve and visualize the impact events that occurred during a simulation run.
MO20	The Simulator shall allow the user to export the impact events to an external file in .CSV format.

Requirements for Scripted Mode Events

The Simulator must provide features for the user to write commands (script list) that will deterministically trigger PTC failure events.

Table 58 lists the requirements to be satisfied by the Simulator for Script Mode Events.

Table 58. List of Requirements for Script Mode Commands

Req. ID	Req. Description
SM01	The Simulator shall allow the user to view the existing Script Mode Event Command Lists.
SM02	The Simulator shall allow the user to select an entry from the list and perform an action, per the following: 1. ACTIVATE – The Simulator shall make the selected entry Active. 2. EDIT – The Simulator shall open the selected entry and allow the user to modify the commands in the list (SM03 to SM07). 3. NEW – The Simulator shall add a new entry in the list and: a. The Simulator shall allow the user to give a name to the entry. b. The Simulator shall allow the user to modify the commands in the entry (SM03 to SM07). 4. DELETE – The Simulator shall remove the Active entry, after confirmation of the action from the user. 5. RENAME – The Simulator shall allow the user to change the name of the selected entry. The name of an entry in the list shall be alphanumeric with up to 40 characters.
SM03	The Simulator shall allow the user to add, remove and modify command lines in the entry that has been selected by the user to be edited.
SM04	The Simulator shall allow the user to save an entry that is being edited as a new entry in the list.
SM05	The Simulator shall trigger events as per the script command line during the simulation, per the triggering configuration of each event type (IO04 and MO01).
SM06	The Simulator shall allow the user to configure scripts to trigger Individual PTC Operation Impact events in any of the following ways: • On a specific train on a specific day at a specific time in the simulation • On a specific train at a specific point on a specific day in the simulation • On a specific train after a specific number of train miles after start of simulation • On a specific train after a specific number of train hours after start of simulation • The user can optionally define how long (in hours and minutes) it will take for the event to be restored.

Req. ID	Req. Description
SM07	The Simulator shall allow the user to configure scripts to trigger WIU Failure events. Each command line includes: • Specific WIU location, which can be a Control Point, an Intermediate Signal or a monitored switch. • Specified day at a specified time in the simulation that the event is to occur. • The user can optionally define how long (in hours and minutes) each WIU will be inoperative until it is restored to normal operation.

Requirements for Configurable Signal Rules

One of the potential improvements with the deployment of PTC can come from eventual changes in signal rule instructions given to train engineers.

One of the envisioned cases would be a change in signal rules to no longer require a speed reduction for approach signal aspects in PTC (e.g., Approach + Advance Approach), referred to as Enhanced Overlay PTC (EO-PTC).

Figure 65 shows the speed profile (dashed black lines) that a train moving towards a signal with Restricted Speed (RSR) with Advance Approach and Approach signal aspects ahead as compared to the speed that would be enforced purely based on the train braking curve, as calculated by the onboard system (dashed green line).

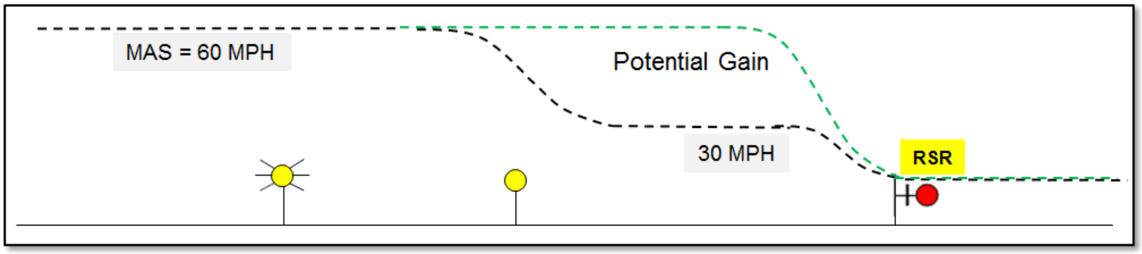


Figure 65. Illustration of Potential Benefit of Modified Signal Rules for Approach Signals with PTC in Passenger Trains

To provide flexible ways for the user to explore any potential changes in signal rules, the Simulator shall essentially provide features to allow the user to configure and select sets of signal rules for a network model flexible enough to create sets of rules that can simulate a scenario like the one illustrated in Figure 65.

Table 59 lists the requirements to be satisfied by the system under this group.

Table 59. Requirements for Configurable Signal Rules

Req. ID	Req. Description
CR01	The Simulator shall allow the user to create/select/edit multiple set of signal rules for a network model.

Req. ID	Req. Description
CR02	The Simulator shall allow the user to associate a set of signal rules to signaling devices configured in the tracks, which can apply to: • The entire model; or • Designated subdivisions within the network and/or to designated segments (between control points or model nodes) within one or more subdivisions. Note that for the same model several sets of signal rules can be in effect, but only one at a time for a portion of track.
CR03	The Simulator shall allow the user to easily display and toggle among sets of signal rules associated with the tracks.

Requirements for Fallback Operation

There are different rules for the operation of a train with PTC disengaged/cut-out or not equipped with PTC (PTC inactive), herein referred to as PTC Fallback Mode, based on the following combination of items:

- Type of system control configured for the tracks (Block Signal Control or Non-Signaled Territory).
- Conditions ahead of the train that is operating in PTC Fallback Mode.
- Whether field signals are retained for fallback operation.
- The type of PTC control method: PTC-Overlay, QMB and FMB

Under normal operations in a CTC controlled territory, the OBC applies a target of the most restrictive aspect for that signal (e.g., a Stop and Proceed, Restricting, or a Stop) at each WIU site (control point and intermediate signal) until it receives a status message from the WIU containing the signal aspect and, if applicable, the switch status, at which point the stop target is removed and the appropriate target is placed per the WIU status message.

For a train to operate in PTC Fallback Mode under the current PTC deployment, there are specific rules (such as train stop, proceed at Restricted Speed until next signal block and resume) that have to be followed. Those operations are based on 49 CFR Part 236, Subpart I.

In CTC controlled territory where signals are retained, it is assumed that the train engineer can see and abide to the signal aspects displayed in the field. If the signals are removed from the field, it is assumed that trains will operate under Track Warrant Control, with voice authorization issued by the dispatcher. In such condition, speed restrictions apply depending on the train type.

In non-signaled territory, movement authority boundaries will be controlled the same for trains with and without operating PTC; i.e., TWs will be issued between sidings, junctions and other named points.

For territories where FMB is deployed and signals are removed, trains operating in PTC Fallback Mode will be dispatched under TWC. Trains with operating PTC that are following trains in PTC Fallback Mode in FMB will also have to be dispatched under TWC, as the location of the train ahead cannot be obtained.

Table 60 lists the various combination of scenarios and the fallback operations.

Table 60. List of Operational Scenarios and Their Fallback Operation

Train Control and Field Configuration	PTC Fallback Operation
PTC Overlay – TWC no Block Signals	_Train is dispatched by TW (voice). _Trains operate at a speed not exceeding 40 mph; 30 mph if carrying PIH materials [per CFR 236.1029(b)(1)].
PTC Overlay – TWC with ABS	_Passenger trains operate at a speed not exceeding 59 mph (per CFR 236.1029(b)(2)(i)). _Freight trains carrying PIH materials operate at a speed not exceeding 40 mph (per CFR 236.1029(b)(2)(ii)). _Other freight trains operate at a speed not exceeding 49 mph (per CFR 236.1029(b)(2)(iii)).
PTC Overlay – CTC– Field signals kept in place.	_Passenger trains operate at a speed not exceeding 59 mph (per CFR 236.1029(b)(2)(i)). _Freight trains carrying PIH materials operate at a speed not exceeding 40 mph (per CFR 236.1029(b)(2)(ii)). _Other freight trains operate at a speed not exceeding 49 mph (per CFR 236.1029(b)(2)(iii)).
PTC Overlay – CTC – All field signals removed.	_Train is dispatched by TW (voice). _Trains operate at a speed not exceeding 40 mph; 30 mph if carrying PIH materials [per CFR 236.1029(b)(1)].
PTC Overlay – Cab signaling territory	Trains operate as per cab signal, but not exceeding 79 mph. (per CFR 236.1029(b)(3)).
QMB – All field signals removed.	1) Operation of train that has PTC inactive: _Train is dispatched by TW (voice). _Trains operate at a speed not exceeding 40 mph; 30 mph if carrying PIH materials [per CFR 236.1029(b)(1)]. 2) Operation of train that is following train with PTC inactive: _Following train is not affected (track circuits continue to inform the position of train ahead in a vital way).
QMB – Field signals kept in place.	_Passenger trains operate at a speed not exceeding 59 mph (per CFR 236.1029(b)(2)(i)). _Freight trains carrying PIH materials operate at a speed not exceeding 40 mph (per CFR 236.1029(b)(2)(ii)). _Other freight trains operate at a speed not exceeding 49 mph (per CFR 236.1029(b)(2)(iii)).

Train Control and Field Configuration	PTC Fallback Operation
FMB – All field signals removed.	1) Operation of train that has PTC inactive: _Train is dispatched by TW (voice). _Trains operate at a speed not exceeding 40 mph; 30 mph if carrying PIH materials [per CFR 236.1029(b)(1)]. 2) Operation of train that is following train with PTC inactive: _Train behind operates under TW (voice) as there is no way for the onboard computer to know the position of train ahead (track circuits are removed).

Table 61 contains the requirements for fallback operation, including specific operation rules and speed restrictions that are applied under each case.

Table 61. Requirements for PTC Fallback Operations

Req. ID	Req. Description
FO01	The Simulator shall allow the user to set the configuration of field signals under fallback operation (FO01-CFS) for CTC signaled territories, to be one of the following: 1. All signals are kept operational (Intermediate and Absolute signals). Train engineers operating a train in Fallback Mode will be able to see the signal aspects and operate per normal CTC operation. 2. All signals are eliminated. Trains in Fallback Mode will be dispatched per TWC rules.
FO02	The Simulator shall allow the user to indicate the configuration of field signals for fallback operation (FO01-CFS) for the following: • An entire subdivision • A group of subdivisions • The entire model
FO03	The Simulator shall allow the user to visualize the configuration of field signals under fallback operation (as per FO01-CFS), showing the colors of the tracks based on their expected fallback operation.
FO04	The Simulator shall allow the user to specify the minimum (FO04-MIN) and maximum (FO04-MAX) duration of time (in minutes and seconds) that a train must wait to restore operations after a preceding train has cleared the Control Block ahead. Default value is 3 minutes for FO04-MIN and 5 minutes for FO04-MAX.
FO05	When a train disengages or is cut-out from PTC and starts operating in PTC Fallback Mode, the Simulator shall operate the train to end of the current Control Block at a speed not exceeding Medium Speed (SC05-MS).

Req. ID	Req. Description
FO06	When a train is operating in PTC Fallback Mode in a CTC signaled territory where all signals are kept operational for fallback operation (per FO01-CFS), the Simulator shall operate the train in PTC Fallback Mode per the following, after the train reaches the end of the Control Block where it started operating in PTC Fallback Mode: 1. Passenger trains operate at a speed not exceeding 59 mph. 2. Freight trains carrying PIH materials operate at a speed not exceeding 40 mph. 3. Other freight trains operate at a speed not exceeding 49 mph.
FO07	When a train is operating in PTC Fallback Mode in a cab signal territory, the Simulator shall operate the train as per cab signal, but not exceeding 79 mph, after the train reaches the end of the Control Block where it started operating in PTC Fallback Mode.
FO08	The Simulator shall operate a train following another train that is in PTC Fallback Mode in a territory where all signals are retained for fallback operation (per FO01-CFS) per normal signal aspect indication.
FO09	When a train is operating in PTC Fallback Mode in a non-signaled territory or in a CTC signaled territory where signals are not retained for fallback operation (per FO01-CFS), the Simulator shall operate the train per the following: 1. Train will operate at a speed not exceeding 40 mph; 30 mph if carrying PIH materials. 2. If the train reaches the end of a Control Block and the Control Block ahead is occupied by another train, train will stop and wait a random-generated time between user-defined duration times (FO04-MIN and FO04-MAX) after preceding train has cleared the Control Block ahead before resuming operation.
FO10	The Simulator shall operate a train with active PTC that is following another train in PTC Fallback Mode in a non-signaled territory or in a territory where signals are not retained for fallback operation (per FO01-CFS) per the following: 1. If the train behind reaches the end of the Control Block and the train in PTC Fallback Mode has not cleared the Control Block ahead, the train behind must wait a random-generated time between user-defined duration times (FO04-MIN and FO04-MAX) after preceding train has cleared the block ahead and then resume operation at track speed. 2. If the train behind reaches the end of the Control Block and the train in PTC Fallback Mode has already cleared the Control Block ahead, the train behind can resume operation at track speed.
FO11	The Simulator shall operate trains in PTC Fallback Mode only on tracks that are configured with PTC Mode ON.
FO12	The Simulator shall allow the user to display the list of existing PTC Fallback Operation Configurations.

Req. ID	Req. Description
FO13	The Simulator shall allow the user to select an entry from the list and perform an action, per the following: 1. ACTIVATE – The Simulator shall make the selected entry Active. 2. EDIT – The Simulator shall open the selected entry and allow the user to modify the parameters in the list (FO00 to FO08). 3. NEW – The Simulator shall add a new entry in the list and: a. The Simulator shall allow the user to give a name to the entry. b. The Simulator shall allow the user to modify the parameters in the entry (FO00 to FO08). 4. DELETE – The Simulator shall delete the Active entry, after confirmation of the action from the user. 5. RENAME – The Simulator shall allow the user to change the name of the selected entry. The name of an entry in the list shall be alphanumeric with up to 40 characters.
FO14	The Simulator shall allow the user save an entry that is being edited as a new entry in the list.

Phase 2 Functional Requirements for PTC Improvements

Introduction

This section describes the requirements needed to simulate methods of train control based on the principle of moving block that could be implemented by railroads in their PTC deployment.

Two concepts of train control methods are envisioned:

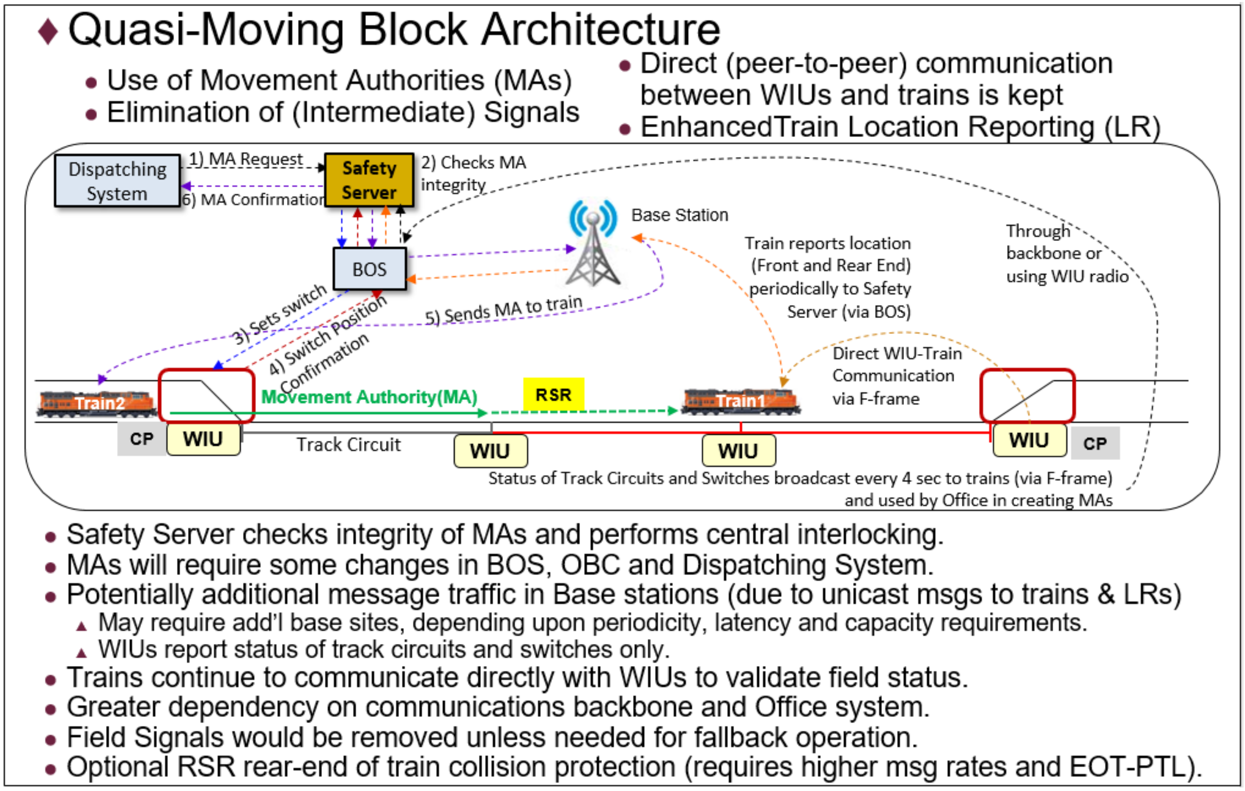
1. QMB – A method based on centralized Movement Authorities (MA) sent to trains and that still relies on fixed blocks in the field (such as track circuits) as primary source of train location.
2. FMB – A method where train location is determined by the trains themselves, i.e., does not depend on fixed block (such as track circuits) to determine the tracks trains are occupying.

The two methods are detailed in the next sections.

Requirements for Quasi-Moving Block Operation

For the purpose of this project, the QMB, a limited moving block design that relies on the existence of track circuit blocks, will be adopted as a potential intermediate design between conventional fixed block (such as CTC) and FMB systems.

In this method of train control, MAs are created in the dispatching system, verified by a Safety Server, which also implements the interlocking logic to each train under the control of the system. The Safety Server uses the position of the trains (front- and rear-end) and the status of the track circuits and switches to update/send the MAs. The OBC receives the MAs and compares it with the status of field devices received directly from the WIUs. As a train approaches the next train ahead, it verifies its distance to the rear-end of the train ahead, and when in close proximity, the train ahead will start reporting its location periodically with a high frequency, so the OBC of the train behind can calculate an approaching distance that allows the train behind to approach safely. When trains are operating in the same track circuit, the speed of the following train is limited to Restricted Speed, as there is no way to determine whether there is a broken rail between the two trains. Figure 66 illustrates the overall architecture of this method of train control.



◆ Quasi-Moving Block Architecture

- Use of Movement Authorities (MAs)
- Elimination of (Intermediate) Signals
- Direct (peer-to-peer) communication between WIUs and trains is kept
- EnhancedTrain Location Reporting (LR)

- Safety Server checks integrity of MAs and performs central interlocking.
- MAs will require some changes in BOS, OBC and Dispatching System.
- Potentially additional message traffic in Base stations (due to unicast msgs to trains & LRs)
  - ▲ May require add'l base sites, depending upon periodicity, latency and capacity requirements.
  - ▲ WIUs report status of track circuits and switches only.
- Trains continue to communicate directly with WIUs to validate field status.
- Greater dependency on communications backbone and Office system.
- Field Signals would be removed unless needed for fallback operation.
- Optional RSR rear-end of train collision protection (requires higher msg rates and EOT-PTL).

Figure 66. Illustration of the Architecture of the QMB Method of Train Control

This method of train control can be abstracted to a simplified model for simulation where components such as WIUs, base stations, safety server and BOS are not included. This method of operation would be similar to a CTC operation without intermediate signals.

Figure 67 illustrates the sequence of events under a simplified model for this method of operation in a signaled territory:

1. The Dispatcher creates a route for Train 1 between two control points (CP1 and CP2).
2. The system internally truncates this route into an MA, based on the (dynamic) status of occupation blocks ahead of the train.
3. As Train 1 moves, a second route is aligned for Train 2 between the same two control points.
4. The system creates a MA for Train 2 up to the last unoccupied block behind Train 1.

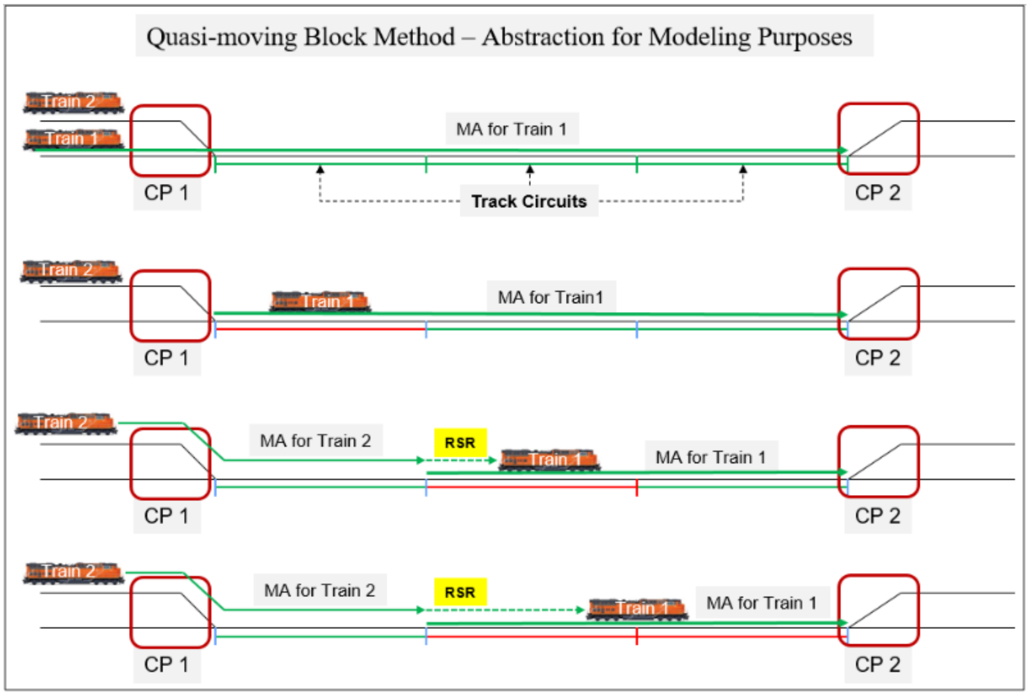


Figure 67. QMB Abstraction – Sequence of MAs

Based on the QMB principle, the concept of block occupancy that exists in a CTC territory will remain; however, it is not necessarily associated to the existence of a signal (such as absolute or intermediate signals) anymore, as the elimination of signals is an option with QMB. This means that between Control Point locations, the Simulator shall be able to allow the configuration of multiple Occupancy Blocks (OB) that, for practical purposes would represent actual track circuits in the field, as illustrated in Figure 68.

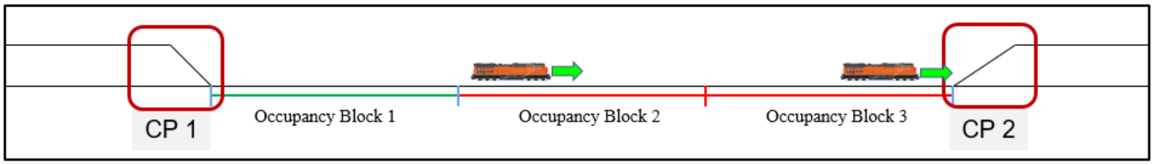


Figure 68. Illustration of Occupancy Blocks in QMB

It is envisioned that the Simulator will provide features that will facilitate the analysis of what-if scenarios – for example, adding OBs between Control Points by splitting existing OBs into multiple individual OBs, as illustrated in Figure 69. Notice that it is more likely that the railroads may split existing track circuits into two new OBs, and no more than that for practical reasons, however, it will be up on the user to configure as many OBs as desired between Control Points.

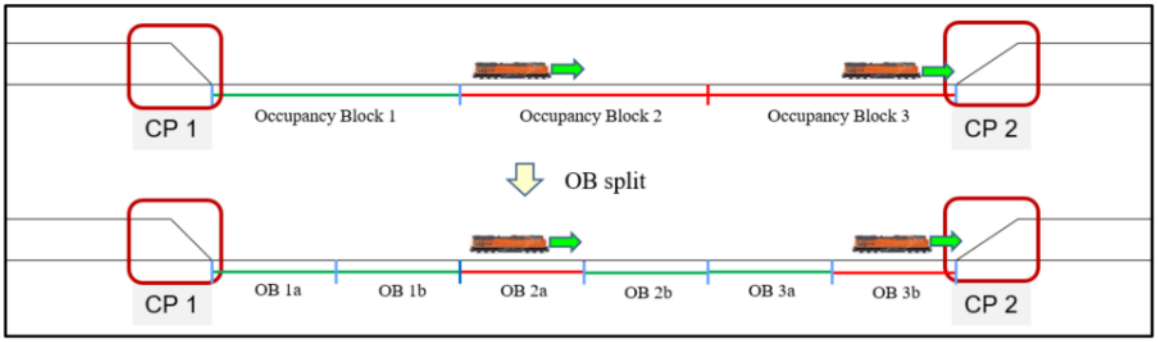


Figure 69. Illustration of Addition of OBs between Control Points in QMB

It is also expected that the Simulator will allow a user to select an existing model created with CTC configuration or with non-signaled tracks and convert it to be QMB controlled territory.

Table 62 lists the requirements to be satisfied by the system under this group.

Table 62. Requirements for Quasi-Moving Block Operation

Req. ID	Req. Description
QM01	The Simulator shall allow the user to configure OBs for a portion of the track. The user shall be able to: 1. EDIT: The Simulator shall allow any OBs configured in the portion of track selected to have its configuration modified. 2. ADD: The Simulator shall allow the user to add a new OB to a portion of the track selected by the user. 3. DELETE: The Simulator shall allow the user to delete an OB from a portion of the track selected by the user. Under options EDIT and ADD, the Simulator shall allow the user to configure an OB, by inputting the following information: • Initial Milepost (numeric, two decimal digits) • Final Milepost (numeric, two decimal digits) When adding an OB to a selected portion of track, the Simulator shall set the initial and final mileposts by default to the same initial and final mileposts of the selected portion of track. The Simulator shall not allow the user to EDIT or ADD an OB that would overlap with another OB. The Simulator shall allow the Initial of Final Milepost of the OB to be at the same location as the Initial or Final Milepost of another OB. The OB shall be contained within the portion of track selected by the user. An OB can be defined for the following components: 1. An entire continuous section of track between two consecutive switches 2. A portion of continuous section of track between two consecutive switches; i.e., between two user-identified mileposts or between a user-identified milepost and a switch

Req. ID	Req. Description
	3. A turnout 4. A crossover 5. A diamond
QM02	The Simulator shall allow the user to perform the functions described in QM01 either by editing a configuration file or by interacting with the graphical interface (point and click).
QM03	The Simulator shall allow the user to automatically create OBs for a selected area (group of tracks). Under this option, the Simulator shall create OBs per the following: 1. In a signaled territory area, one OB for each continuous section of tracks between Signal Blocks within the selected area 2. In a non-signaled territory area, one OB for each continuous section of tracks between Control Blocks within the selected area 3. One OB for each turnout, crossover and diamond within the selected area
QM04	The Simulator shall allow the user to split an existing OB (or group of OBs) into multiple OBs with equal size, by dividing OB's original size per a number informed by the user (QM04-NOB).
QM05	The Simulator shall provide a graphic display of the OBs that are configured in the model.
QM06	During a simulation run, the Simulator shall determine the status of occupation of each OB, per the following: 1. Unoccupied: When no portion of any train is within the OB limits. 2. Occupied: When a portion of at least one train is within the OB limits.
QM07	The Simulator shall allow a train to occupy an Unoccupied OB ahead even if there are other trains in the same Control Block of the Unoccupied OB but moving in the same direction.
QM08	The Simulator shall not allow a train to occupy an Unoccupied OB ahead if there is another train in the same Control Block of the Unoccupied OB authorized to move in opposite direction.
QM09	The Simulator shall allow the user to trigger the generation of output file containing details of train movements for a selected train or a group of trains or all trains in the model.
QM10	The Simulator shall generate an output file containing the information of train movements at every second containing for the trains selected by the user (per QM07): 1. Identification of the train 2. Timestamp 3. Location of the train (head-end and rear-end) 4. Distance to the next train ahead if there is a train ahead along the current train route. 5. Identification of the OBs occupied by the train.

Requirements for Full-Moving Block Operation

The general principle of the moving block concept essentially allows trains moving in the same direction to ideally be separated by just the footprint of the train ahead (location of the train head and rear-end) and the braking distance of the train behind, as illustrated in Figure 70.

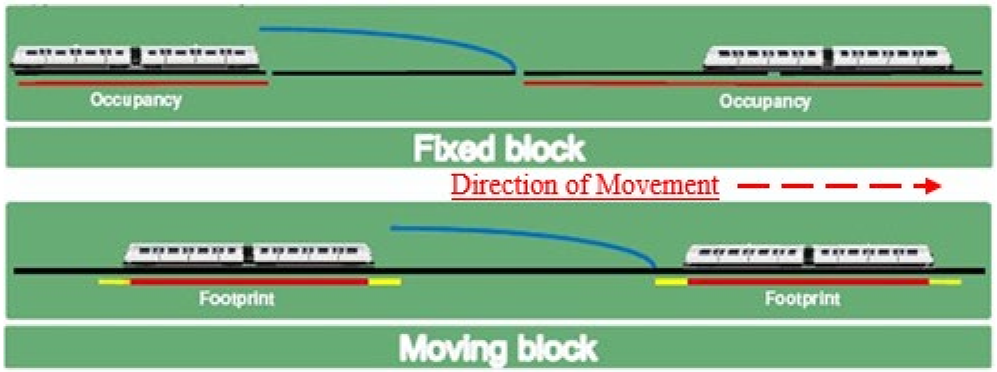


Figure 70. Illustration of Fixed Block and Moving Block Concepts

Figure 71 illustrates additional components that may increase the separation distance between the two trains, depending on how the system is implemented:

- Error Margin: This is related to potential errors in the onboard location determination system.
- Latency Effect: This would be specified in time and is related to the latency that a message containing the information of location of the train ahead (front- and rear-end) is conveyed to the train behind.

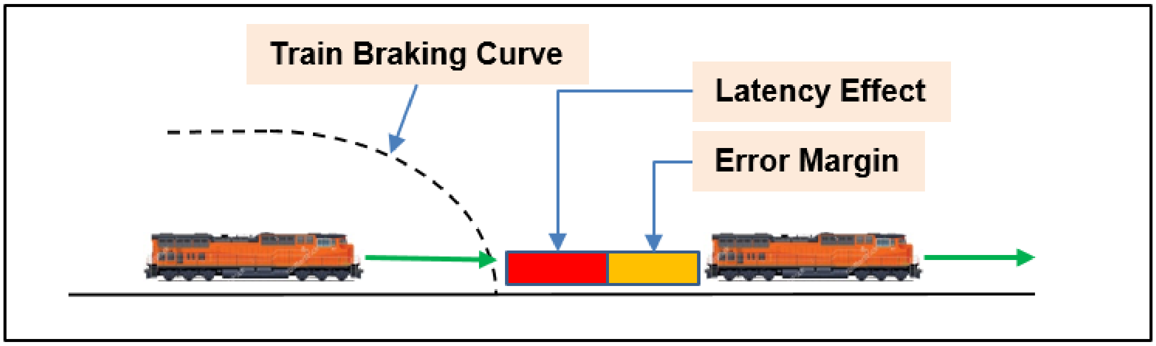


Figure 71. Illustration of All Elements that Contribute to Train Separation Distance Between Trains in Following Moves in a Moving Block Operation

Two components contribute to the Latency Effect in following train moves:

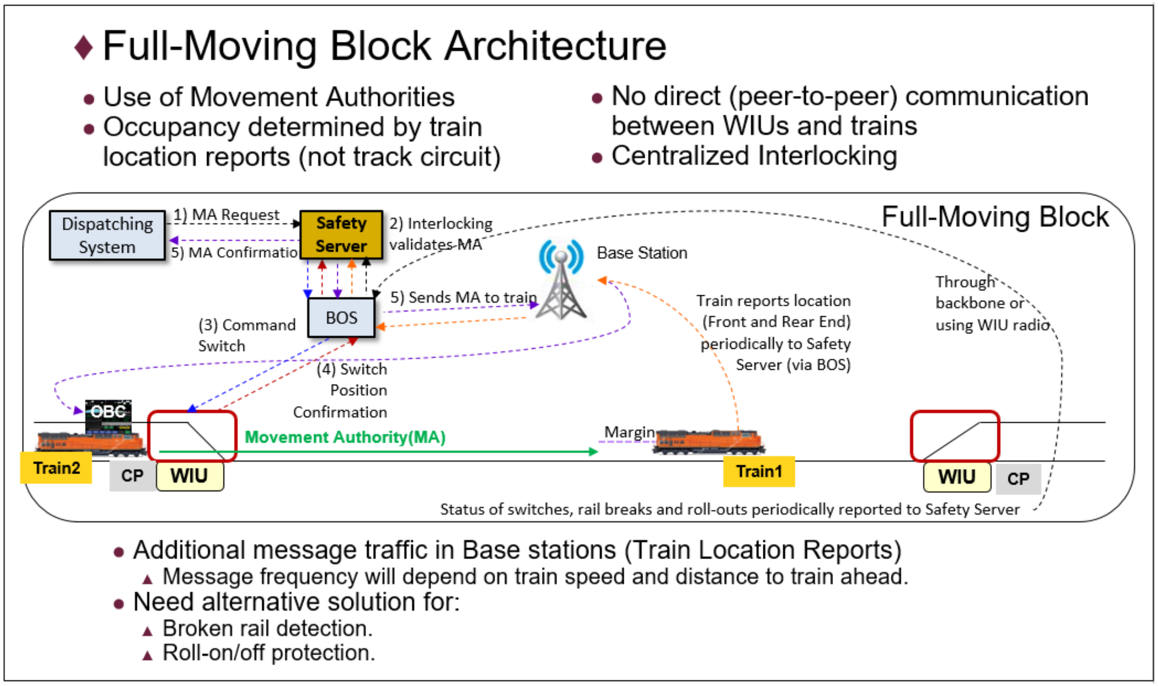
1. Intrinsic Latency: This is the delay caused by the communication path the message will traverse until destination (from the time it is originated in one train until it is received by another train)
2. Frequency Rate: This informs how frequently trains will notify their location to the system. A train behind in a following movement will always assume that the rear-end of the train ahead is at the location informed by the last message received. As this

information can be as old as the frequency rate, additional separation will be added between trains.

Based on the above, the Latency Effect will be as small as the Intrinsic Latency at the time the train ahead reports its position (best-case scenario) and as large as the sum of the two components (Intrinsic Latency + Frequency Rate) at a time just before the train ahead reports its position (worst case scenario). Assuming that the latency is 4 seconds and the Frequency Rate is 16 seconds, and the train ahead is moving at 36 mph; a train behind would be assuming in a worst-case scenario (just before a new train position report for the train ahead is received) that the train ahead is 20 seconds behind of where it actually is, which would be 0.2 mile behind its current location. If the train ahead is operating at 18 mph, the worst-case scenario is reduced to 0.1 mile.

It must be assumed that the Latency Effect will be the sum of the two components (i.e., the worst-case scenario) because for practical purposes in actual train operation, it is not expected that the train engineer will be adjusting speed to conform to the best- and worst-case scenarios, but is keeping the train separation based on the worst case scenario.

Like the QMB operation, a Safety Server will be issuing periodic MAs to each train under PTC control. Figure 72 illustrates the overall architecture of this method of train control.



♦ Full-Moving Block Architecture

- Use of Movement Authorities
- Occupancy determined by train location reports (not track circuit)
- No direct (peer-to-peer) communication between WIUs and trains
- Centralized Interlocking

- Additional message traffic in Base stations (Train Location Reports)
  - ▲ Message frequency will depend on train speed and distance to train ahead.
- Need alternative solution for:
  - ▲ Broken rail detection.
  - ▲ Roll-on/off protection.

Figure 72. Illustration of the Architecture of FMB Method of Train Control

For the purposes of simulation, the model for the method of train control can also be abstracted as per the following:

- The location of each train (front- and rear-end) is calculated at every instant (as trains move).
- The location of each train is reported periodically at a rate determined by the user (in matter of seconds). This is the last reported position of a train.

- Based on a train’s granted route and on the last reported position of the train ahead, the system calculates the train’s MA.
  - If there are no other trains on the tracks between the current track location and the end of the train’s authorized route, the train can proceed per maximum authorized or achievable speed based on civil speed limits and speed restrictions.
  - If there are other trains moving in the same direction, the limit of the MA is based on the location of the rear-end of the next train ahead. The calculation of the MA also includes a safety margin and latency effect.
- The system calculates the train’s braking curve based on train speed, consist characteristics, and track grade.
- Train movements are enforced per their MAs and braking curve.

This method of train control can also be abstracted to a simplified model for simulation, which would be similar to a CTC operation without intermediate signals. The main difference when compared with the QMB method is that track circuits are eliminated; thus, the MA for a certain train is limited to the rear-end of the next train ahead moving in the same direction including the margins to the rear-end explained earlier in this section. Figure 73 illustrates the sequence of events under a simplified model for the FMB method of operation.

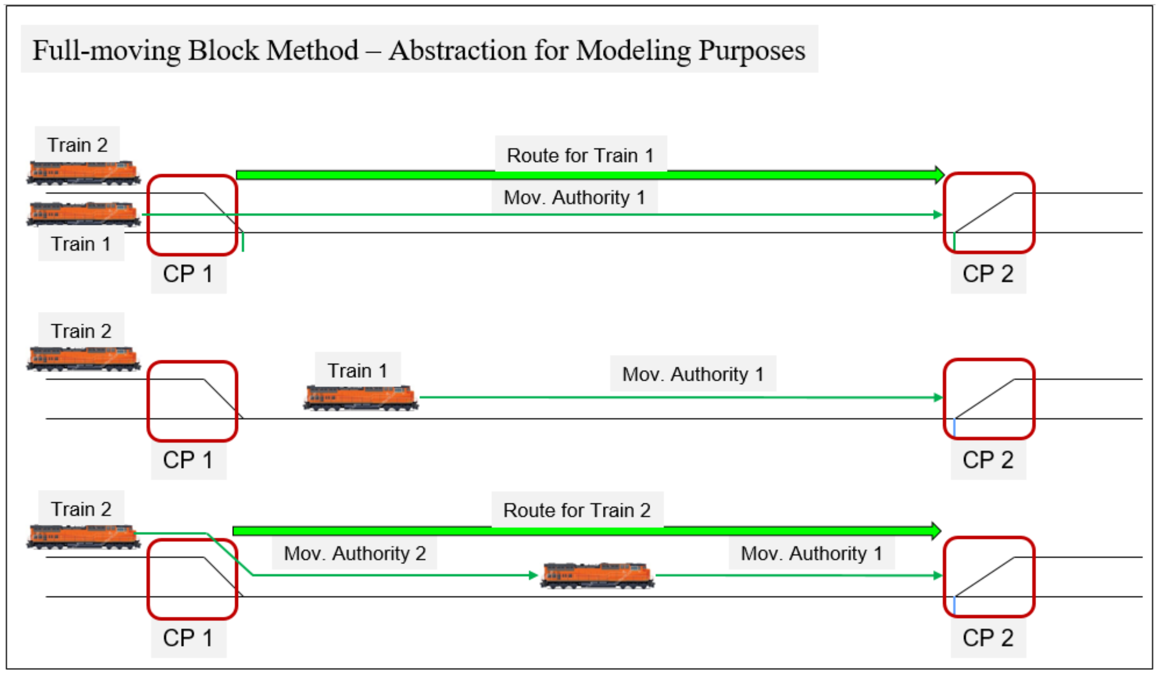


Figure 73. FMB Simplified Model Sequence in a Signaled Territory

A train following another train ahead cannot be authorized to move beyond the rear- end of the train ahead. As illustrated in Figure 73, each train reports its location to a Safety Server, who in turn issues MAs to trains based on the location of all trains.

The frequency rate that a train will report its location depends on its separation from a train following behind. If the separation from its rear-end (including margins) to the following train’s head end is less than the following train’s braking distance plus the distance the following train travels in a pre-determined duration of time (e.g., 70 seconds), the train behind is said to be in a Close Following Move (CFM) to the train ahead. Under this condition, the train ahead will report its location with a higher frequency rate than when there is no train behind in CFM. Figure 74 illustrates a train following a preceding train in a CFM condition. The Simulator shall indicate when such condition happens to a train as this will be valuable information to be used in further analysis of train message traffic.

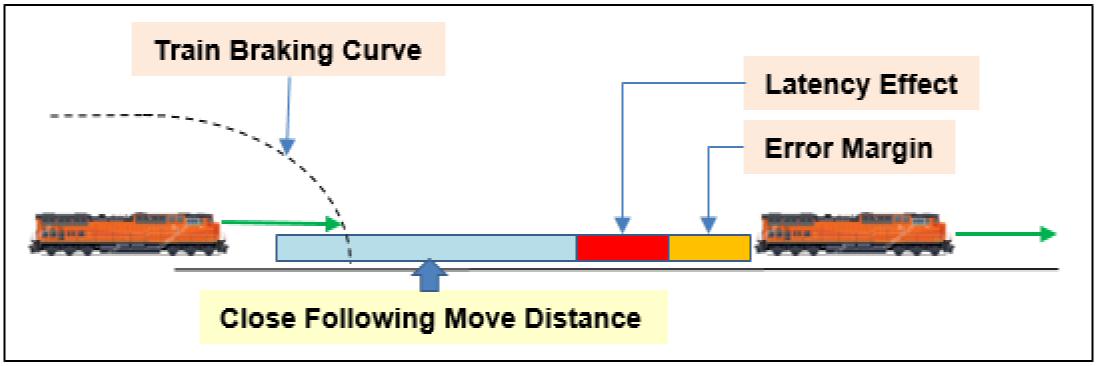


Figure 74. Illustration of Close Following Move Condition

Table 63 lists the requirements to be satisfied by the system under this group.

Table 63. Requirements for FMB Operation

Req. ID	Req. Description
FM01	The Simulator shall allow the user to specify the Error Margin (in feet) to be added to the rear-end of the train to account for errors in the train determination location system (FM01-SMR). Default value is 100.
FM02	The Simulator shall allow the user to specify the Intrinsic Latency (in seconds) that defines how long it will take for a train location message from a train to be delivered to other trains (FM02-ITL). Default value is 2.
FM03	The Simulator shall allow the user to specify the Update Rate (FM03-UPR) that trains report their location in seconds. Default value is 16 seconds.
FM04	The Simulator shall allow the user to configure Control Point locations for FMB for a portion of track in the same fashion as done for a CTC territory or for a dark territory area.
FM05	The Simulator shall allow the user to adopt the location of Absolute Signals configured for a CTC territory and/or the location of Signaled Switches configured for dark territory as the Control Points to be used for FMB, per the following options: • For an entire subdivision • For a group of subdivisions • For the entire model
FM06	The Simulator shall allow the user to configure the duration (in seconds) used to calculate the separation that determines a CFM condition of a following train (FM06-CFS). Default value is 70 seconds.

Req. ID	Req. Description
FM07	During a simulation run, the Simulator shall calculate the location of each train at every instant per the following: 1. Head-End: Current location of the front of the train as calculated per the Simulator. 2. Rear-end: Current location of the rear-end of the train, based on the head-end, train length, and the following margins: a. Error Margin (FM01-SMR) b. Distance train would travel at current speed during Intrinsic Latency (FM02-ITL) time. c. Distance train would travel at current speed during train update rate (FM03-UPR) time.
FM08	During a simulation run the Simulator shall determine if a train moving in a certain direction is in a CFM to a train ahead moving in the same direction on the same track, using the following information: • Head-end location of the train behind • Rear-end location of train ahead • CFM separation duration (FM06-CFS) The Simulator shall compare the time that it will take for the head-end of the train behind to reach the location of the rear-end of the train ahead if train behind keeps current train speed. If the calculated time is below FM06-CFS, train behind is in CFM.
FM09	During a simulation run, the Simulator shall calculate the train braking curve (as per TB01) considering the following: • The MAS of the tracks along the train authority • The TSRs imposed to the tracks along the train authority. • If there is another train ahead moving in the same direction along the current train route, the Simulator shall calculate the braking curve so that the train stops at the rear-end of the train ahead. – Otherwise (i.e., no train within the current train route), the braking curve shall be calculated so that the train stops at the end of the current train authority, per TB01_PBC.
FM10	The Simulator shall allow the user to trigger the generation of output file containing details of train movements for a selected train or a group of trains or all trains in the model.
FM11	The Simulator shall generate an output file containing the information of train movements per FM10, including: • Identification of the train • Timestamp • Location of the train (head- and rear- end)

Req. ID	Req. Description
	- Distance to the next train ahead if there is a train ahead along the current train authority, based on the rear-end location of train ahead. - Identification of the next train ahead if there is a train ahead along the current train authority. - CFM status of the train

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Abbreviations and Acronyms

Abbreviation	Definition
ABS	Automatic Block Signaling
AG	Advisory Group
ATC	Automatic Train Control
BER	Bit Error Rate
BOS	Back-Office System
BSS	Berkeley Simulation Software
CAD	Computer-Aided Dispatching
CFM	Close Following Move
CIXL	Centralized Interlocking
ConOps	Concepts of Operation
CP	Control Point
CTC	Centralized Traffic Control
CTC	Centralized Traffic Control
DP	Distributed Power
DUA	Dense Urban Area
EO-PTC	Enhanced Overlay Positive Train Control
FMB	Full-moving Block
FOAD	Fiber optic acoustic detection
GDOP	Geometric Dilution of Precision
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HRCTC	Higher Reliability and Capacity Train Control
IS	Information System
ITC	Interoperable Train Control
LOS	Line-Of-Sight
MAS	Maximum Authorized Speed
MBS	Manual Block System
MTBDE	Mean Time Between Downing Events
MTTR	Mean Time To Repair
NGTC	Next Generation Track Circuit

Abbreviation	Definition
NRFICI	National Rail Freight Infrastructure Capacity and Investment
OB	Occupation Block
OBC	Onboard Computer
OBRD	Onboard Broken Rail Detection or Onboard Broken Rail Detector
PTC	Positive Train Control
PTCEA	PTC Enforceable Authority
PTCIE	PTC Impact Event
PTL-EOT	Positive Train Location – End Of Train
QMB	Quasi-moving Block
RAM	Reliability, Availability and Maintainability
RF	Radio Frequency
ROI	Return Of Investment
RSR	Restricted Speed Restriction
RTC	Rail Traffic Controller
RVCCM	Requirements Verification Conditions and Criteria Matrix
SG	Signal Group
SysRs	System Requirement Specification
TOES	Train Operation and Energy Simulation
TSR	Temporary Speed Restriction
TUL	Track Utilization Level
TWC	Track Warrant Control
WIU	Wayside Interface Unit
WSM	Wayside Status Message
WSRS	Wayside Status Relay Service