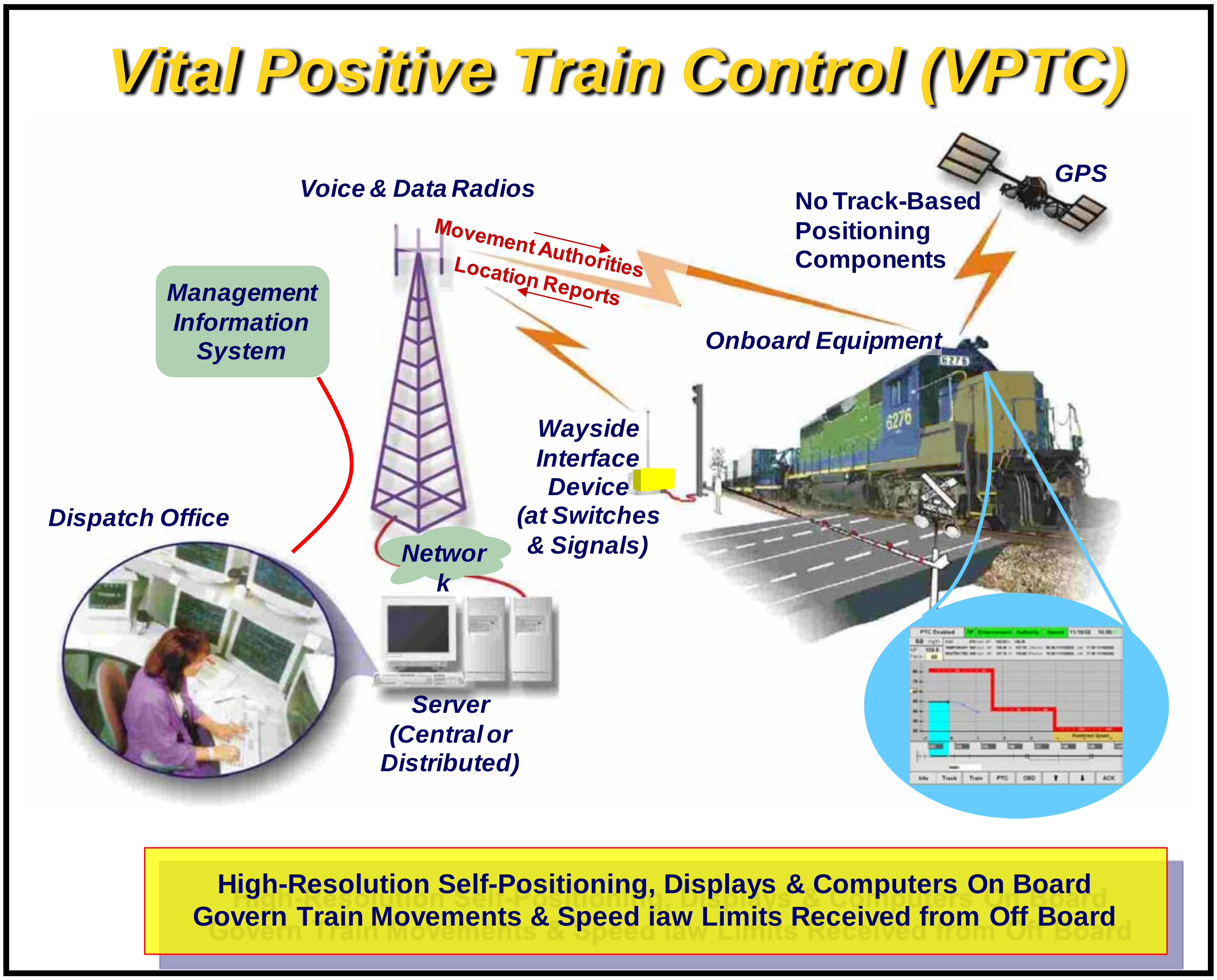
U.S. Department of Transportation

Federal Railroad Administration

Vital Positive Train Control Research and Development—Final Report

Office of Railroad Policy and Development
Washington, DC 20590



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13. ABSTRACT

The Transportation Technology Center, Inc. (TTCI), in cooperation with, the Federal Railroad Administration (FRA), the Railroad Research Foundation (RRF), and the Mission Systems and Sensors (MS2) Division of the Lockheed Martin Corporation (LMC) conducted research and development (R&D) activities for a safety-critical, communications-based train control (CBTC) system. The system R&D was performed under the Vital Positive Train Control (V-PTC) project, and the goal of the project was to field test a fully functional vital PTC system that could be used in revenue service operations. Jointly, TTCI and LMC accomplished activities related to active field testing of the V-PTC system using the track and related facilities at TTC. Test results show significant development success.

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1 square yard (sq yd, yd^2)	=	0.8 square meter (m^2)	1 square kilometer (km^2)	=	0.4 square mile (sq mi, mi^2)
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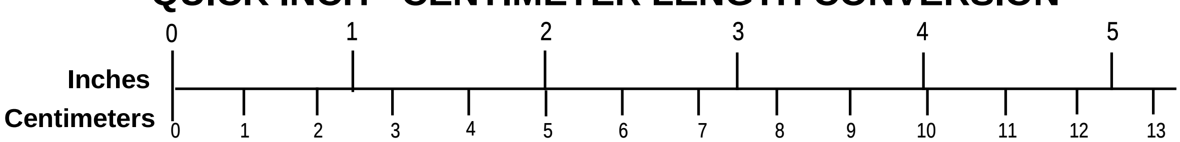

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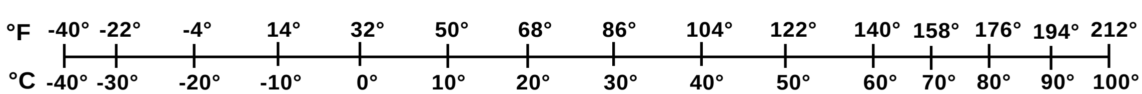

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Executive Summary

The Transportation Technology Center, Inc. (TTCI), in cooperation with the Federal Railroad Administration (FRA), the Railroad Research Foundation (RRF), and the Mission Systems and Sensors (MS2) Division of Lockheed Martin Corporation (LMC), conducted research and development (R&D) activities for a safety-critical, communications-based train control (CBTC) system.

The new system, functionally a second generation positive train control (PTC) system, is designed to use an office-centric architecture based on current and evolving industry PTC communications technologies. R&D was performed under the Vital Positive Train Control (V–PTC) project.

Building on the work of the North American Joint Positive Train Control (NAJPTC) program, the V–PTC project was responsible for developing, building, and testing, a revenue-service-ready, V–PTC system at the Transportation Technology Center (TTC) facility, and demonstrating the system on a revenue service route. It was envisioned that V–PTC, as a PTC system, would provide public benefits by reducing risk to railroad passengers and employees, as well as potentially improving the efficiency of the national railroad network.

The scope of this project included Project Office, Systems Engineer, System Development Integrator and development test support activities. TTCI, as the Project Office, coordinated with LMC, as the System Development Integrator, to manage the project, with input from the V–PTC technical advisory group and FRA. In its role as Systems Engineer, TTCI provided system engineering activities for developing documentation, performing analysis, and completing system specifications. LMC as the System Development Integrator developed and provided the necessary system hardware and software, and it coordinated with TTCI to install system components at TTC for testing.

Jointly, TTCI and LMC undertook activities, meetings, and conferences related to the development of the V–PTC system. These activities included active field testing of the V–PTC system using the track and PTC communications and control infrastructure at TTC's facility. Initially, the project was designed to include system testing on a revenue service route of a participating AAR member railroad, but as the project unfolded, the member railroad elected to use an alternative interoperable PTC system, and the revenue service testing phase was deleted from the project.

The project focused on developing V–PTC locomotive and office PTC segments. These segments were then integrated with a commercially available computer aided dispatch (CAD) system located at TTC, providing one of the earliest integrated PTC CAD/back office server (BOS) combinations in the industry. The locomotive and office segments were also integrated with TTC's wayside segment components, including track infrastructure, wayside signal systems, radio frequency (RF) communications network, and a track database for the Railroad Test Track (RTT). The V–PTC system was designed to meet the key requirements of a PTC system as defined in the Rail Safety Improvement Act of 2008 (RSIA '08).

In compliance with V–PTC technical advisory group and FRA guidance, the project was implemented using an approach based on providing demonstrated incremental progress during the system development cycle. V–PTC functionality development and related testing were distributed throughout five groups of demonstrated and deployable capability.

- Build 1 (Train Location Monitoring) was designed to determine the accurate location and speed of a train without the aid of track circuits and to report these data to the V–PTC Server.
- Build 2 (Server Switch Monitoring) was designed to (1) develop the V–PTC capability to monitor and report the alignment of both powered and hand-operated switches, (2) monitor and report the status of associated On-Station track circuits, and (3) ensure that all of these conditions are reported to the V–PTC Server.
- Build 3 (Switch Warnings and Control) was intended to (1) ensure that all of the data in the previous builds, including switch point position, are transmitted to the onboard display of the locomotive and (2) that the data can be seen and evaluated by the engineer (driver) in the cab of the locomotive.
- Build 4 (Onboard Display of Authority) was intended to (1) verify the capability to remotely control alignments of monitored and powered switches by a dispatcher using the CAD/BOS interface, (2) transmit the information monitored in Builds 1 and 2 from the V–PTC BOS to the CAD system using the interface, and (3) display all authorities entered by the dispatcher to the engineer in the cab of the locomotive.
- Builds 5–8 (Reactive Enforcement of Speed and Authority Limits) encompassed system capabilities associated with movement authorities and related functionalities.

The builds were developed as a coordinated group and then tested in a single on-track test period in November and December 2009. After completing development activities for Builds 5–8, the project plan was to continue incremental system development until the system had full virtual block functionality. However, because of 2010 funding circumstances, the project emphasis shifted to developing and demonstrating the LMC implementation of the TTCI-developed PTC enforcement braking algorithm (EBA) and to revising the System Requirements Specification (SRS) for Builds 5–8 to include the remaining functionalities needed to provide V-PTC virtual block capabilities.

As part of the V–PTC project's focus on addressing PTC related issues, the V–PTC technical advisory group asked the TTCI team to examine some of the effects of PTC EBAs on freight train operations. During pilot operational use of some other PTC systems, train crews had experienced penalty brake enforcements in situations for which they were not warranted. Some of the affected operational conditions were examined by running simulations using the Train Operations and Energy Simulator (TOES), a validated, widely accepted model for simulating freight train performance in detail. The resulting analysis of the effects of PTC EBAs on freight train operations showed that a PTC EBA that assumes worst-case braking characteristics (no use of independent brake and no use of dynamic brake, which are common assumptions) has the potential to have a significant negative impact on freight railroad operations. The analysis also showed the potential improvement to operations by including independent and emergency braking as part of the PTC enforcement solutions. As a result of this analysis, a separate FRA-sponsored project to further investigate methods for improving PTC EBAs was initiated.

To support the periodic developmental system performance evaluations, TTCI upgraded the existing track, signals, and communications infrastructure at the TTC in Pueblo, Colorado. These upgrades included adding PTC control points (in the form of remotely monitored and controlled switches), a 4,000-foot siding for meets and passes testing, and 900 megahertz (MHz) PTC radio communication systems. Also added were a CAD system and a BOS. The design, installation, and checkout of these upgrades were phased to correlate with the testing needs of the incremental development cycle. An additional benefit of the project is that these enhanced test bed features are available as needed for testing other PTC systems.

For each of the system builds, testing was performed to compare system performance to the related requirements in the SRS. Detailed test reports were produced.[1,2,3,4,5] Portions of these reports are either summarized or directly extracted and used throughout this report. The results show significant development success.

1. Introduction

FRA and the railroad industry are very interested in accelerating the development and deployment of PTC systems that are in compliance with federal regulatory requirements. The National Transportation Safety Board for years placed PTC technology, an advanced train control system, as the most wanted technology to enhance safety in the railroad industry. The RSIA'08 mandated that PTC be installed on intercity passenger, commuter passenger, and most Class 1 freight rail lines by the end of 2015. FRA subsequently codified that with the addition to the Code of Federal Regulations (CFR) Subpart I of 49CFR236.

Through years of R&D by the NAJPTC program, substantial progress was made. Several railroads adopted significant portions of the technology in developing their PTC systems. However, the systems developed by these railroads are overlay systems, and they do not have a central safety server that would enable enhanced functionalities, such as moving block capabilities and protection against propagation of false clears. Moving block technology was identified as a possible business benefit of a PTC system that could potentially increase the capacity of certain lines over that provided by conventional fixed block systems. Also, development of a centralized vital system could benefit the industry by producing a PTC system that could replace aging signal systems without the burden of substantial infrastructure replacement and continued maintenance of extensive wayside systems. As a replacement to provide at least the same safety level as a centralized traffic control (CTC) system, which is a vital signal system, a PTC system would need to be of a fail-safe design, with detection capabilities of all failure modes and closed-loop designs of all safety-critical components.

TTCI, in cooperation with FRA, RRF, and the MS2 Division of LMC, conducted R&D activities for a safety critical, CBTC system. The system, functionally a second-generation vital PTC system, is designed to use an office-centric architecture based on current and evolving industry PTC communications technologies. The system R&D was performed under the V–PTC project and the goal of the project was to field test a fully functional vital PTC system that could be used in revenue service operations.

1.1 Background

Beginning in 2001, the NAJPTC Program, in a partnership with the Illinois Department of Transportation (IDOT), AAR, and FRA, conducted testing between Mazonia and Springfield, Illinois, to verify and validate a vital PTC design. IDOT originally planned to leverage this technology to allow passenger trains to operate at speeds up to 110 miles per hour (mph) along this corridor. However, because of the extensive development time required, IDOT decided in 2006 to install conventional cab signal technologies along the route and withdrew from the partnership. Therefore, FRA and RRF elected to continue development of a vital PTC system elsewhere. With the concurrence of the participants in NAJPTC (FRA, AAR, IDOT, Union Pacific Railroad, and Amtrak), the NAJPTC steering committee was disbanded and a new committee comprised of FRA, RRF, and Norfolk Southern, as an operating railroad representative, was formed as a technical advisory group for a new follow-on project, the V–PTC project. LMC, the NAJPTC System Development Integrator, agreed to provide in-kind services, worth $2 million or more per year for three years, in order to continue development of a V–PTC system. LMC further agreed to cooperate with TTCI (as Project Office for the new V–PTC project) on engineering, system development, and field testing of the follow-on V–PTC system. Functionally, in the follow-on project, LMC SD2 performed as the System Development Integrator and TTCI served as the Project Office, Systems Engineer, and as the field test support agency, providing facilities and expertise for field R&D testing activities.

1.2 Objectives

Building on the NAJPTC development work, the objective of the V–PTC project was to continue developing, testing, and demonstrating a revenue service-ready V–PTC system at TTC, and then to demonstrate the system on a revenue service route. It was envisioned that V–PTC, as a PTC system, would provide public benefits through a reduction in risk to railroad passengers and railroad employees and would potentially improve the efficiency of the national railroad network.

1.3 Overall Approach

The overall approach was to have TTCI develop the V–PTC Concept of Operations[6] and SRS,[7] and to have LMC design, develop, and produce V–PTC system components. The system was developed and tested in incremental builds of increasing capabilities. This incremental development approach enabled the TTCI/LMC team to periodically evaluate system performance to ensure each development phase produced capabilities aligned with the SRS. This approach was used to ensure development of a system of continually increasing complexity had a solid, well examined foundation on which to build.

To support these periodic developmental system performance evaluations and testing of other PTC systems, TTCI upgraded the existing track, signals, and communications infrastructure at the TTC in Pueblo, Colorado. These upgrades included adding PTC control points (in the form of remotely monitored and controlled switches), a 4,000-foot siding for meets and passes testing, and 900 MHz PTC RF communication systems. Also added were a CAD system, a BOS, and PTC test instrumentation. The design, installation, and checkout of these upgrades were phased to correlate with the testing needs of the incremental development cycle.

1.4 Scope

The scope of this project included Project Office, Systems Engineer, System Development Integrator, and development test support activities. TTCI as the Project Office coordinated with LMC as the Systems Development Integrator to manage the project, with input from the V–PTC technical advisory group and FRA. In its role as Systems Engineer, TTCI provided system engineering activities for developing documentation, performing analysis, and completing system specifications. LMC as the System Development Integrator developed and provided the necessary system hardware and software, and it coordinated with TTCI to install system components at TTC for testing. Jointly, TTCI and LMC undertook activities, meetings, and conferences related to the development of the V–PTC system. The V–PTC system was actively tested using the track and PTC communications and control infrastructure at TTC. Initially, the project was designed to include system testing on a revenue service route of a participating AAR member railroad, but as the project unfolded, the member railroad elected to use an alternative interoperable PTC system, and the revenue service testing phase was deleted from the project.

1.5 Organization of the Report

This report is organized in five major sections. Section 1 is the introduction and discusses the project's background, objectives, overall approach, and scope. Section 2 provides a description of the V–PTC system, including the system architecture, the V–PTC server, onboard systems, and communications. Section 3 describes the V–PTC system development cycles, including Build 1 (Train Location Monitoring), Build 2 (Server Switch Monitoring), Build 3 (Switch Warnings and Control), Build 4 (Onboard Display of Authority), and Builds 5–8 (Reactive Enforcement of Speed and Authority Limits). Section 4 provides information about the TTC's PTC Test Bed, including an overview, a description of test bed elements, a summary of the test bed architecture, a review of the upgrades performed in 2009, and a brief description of the documentation package for the upgrades. Section 5 presents an overview of testing for each of the V–PTC build cycles and a summary of the associated test results.

2. V–PTC System Description

This project focused on developing V–PTC locomotive and office PTC segments. These segments were then integrated with a commercially available CAD system located at TTC, providing one of the earliest integrated PTC CAD/BOS combinations in the industry. The locomotive and office segments were also integrated with TTC's wayside segment components, including track infrastructure, wayside signal systems, wayside interface units, RF communications network, and a track database for the RTT. The system was designed to meet the four key requirements of a PTC system, as defined in RSIA '08:

- Prevent train-to-train collisions
- Prevent over-speed derailments
- Prevent incursions into established work zone limits
- Prevent movement of a train through a switch left in the wrong position

2.1 V–PTC System Architecture

The V–PTC system architecture is described in detail in *V–PTC Onboard Train Internal System Architecture*.[8] For the reader's convenience (and with LMC permission), a portion of the report is presented here. The V–PTC system is required to interface with the locomotive crew, the V–PTC Dispatch System, and the Wayside Interface Unit (WIU), and is broken up into two major subsystems, the V–PTC Server, and the V–PTC Onboard. The V–PTC Server and V–PTC Onboard are interconnected through the V–PTC Communications System, which is used to maintain system status and to share data with each other. Figure 1 shows how the V–PTC system functions with the other external systems, and Figure 2 shows the internal structure and architecture of the V–PTC system.

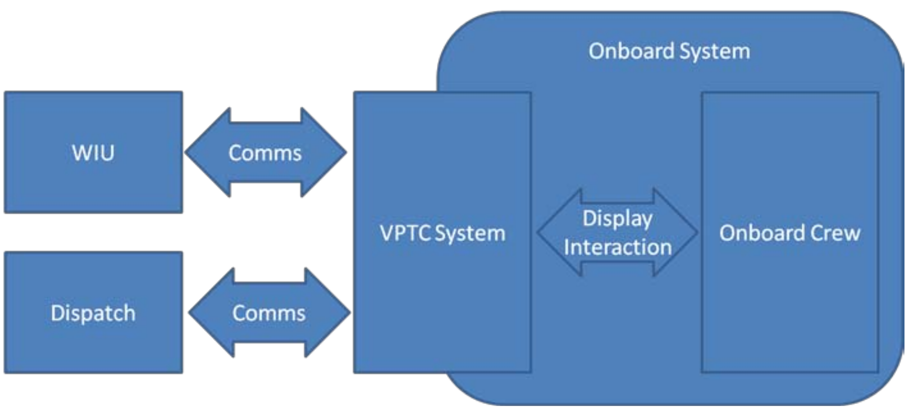

Figure 1. V–PTC System Interaction

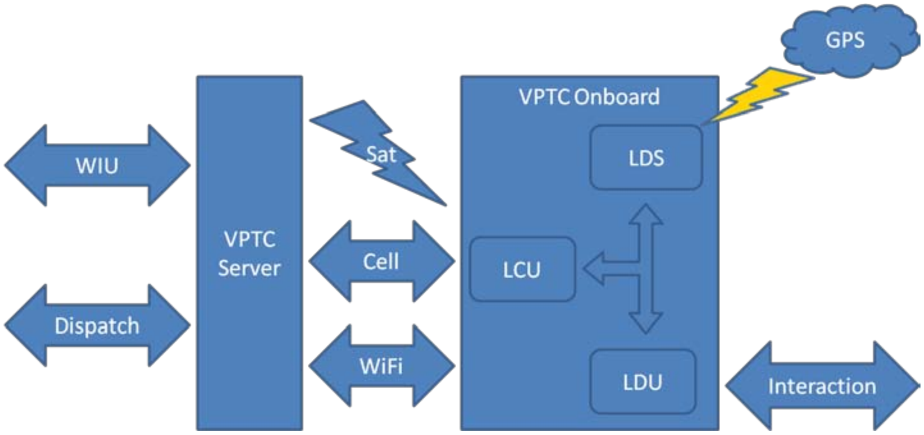

Figure 2. V–PTC System Architecture

2.2 V–PTC Server

The V–PTC Server Subsystem consists of the Authority Management Server (AMS) and connections to the V–PTC dispatch system and the WIU network. The AMS is responsible for determining authority status throughout the V–PTC system territory, authority conflict checking, and distributing the authorities received from the V–PTC Dispatch System as appropriate; the AMS is responsible for stacking and unstacking authorities as required by operating procedures on V–PTC track. Additionally, the AMS is responsible for processing speed bulletins as delivered by the V–PTC dispatch system, determining switch status via WIU reports, and maintaining a track database with all monitored and unmonitored switches for notification to the V–PTC onboard subsystem. The V–PTC server subsystem also provides interactions with any operators and maintainers as required.

In general, the V–PTC server subsystem is responsible for tracking system configurations, determining which system configurations are valid and functioning, processing alerts from the V–PTC Onboard and passing the appropriate alerts and notifications to the V–PTC dispatch system. In the case of powered switches along proposed locomotive routes, the V–PTC server subsystem is responsible for configuring the powered switches such that the locomotive will be able to traverse the route with minimal stoppage.

2.3 V–PTC Onboard

The V–PTC Onboard subsystem is responsible for managing a single locomotive and communicating with the V–PTC server. In general, the V–PTC Onboard System is responsible for ensuring that the locomotive operates in a manner consistent with its authorities (as delivered by the V–PTC server), and with the standing railroad rules and regulations governing the local area surrounding the railway.

The V–PTC Onboard System is responsible for periodically checking internal data and physical components to ensure no data corruption has occurred within the data stored on it. Additionally, the Onboard System is responsible for periodically checking the health of all onboard PTC components stopping the train, and reporting to the V–PTC server if any anomalies are detected.

The V–PTC Onboard System is currently designed to have three major functional units within it: (1) the Location Determination System (LDS), (2) the Locomotive Display Unit (LDU), and (3) the Locomotive Control Unit (LCU). These three major units are expected to interact with the locomotive, locomotive crew, and the V–PTC server. These three units work together and ensure that the locomotive operates in accordance with the authorities granted the locomotive by the V–PTC dispatch system and V–PTC server, as well as the operating rules of the railway.

A functional breakdown of the V–PTC Onboard System is as follows:

- The LCU is responsible for interacting with the V–PTC server and integrating all of the inputs from the LDU, LDS, and V–PTC server to control the locomotive, brake when necessary, and respond to situations as appropriate.
- The LDS is responsible for interfacing with the locomotive sensors and Global Positioning System (GPS) systems to determine current locomotive state and position. Additionally, it is responsible for mapping the locomotive to track or requesting crew assistance (via the LDU) if unable to map to track.
- The LDU is responsible for interacting with the locomotive crew, providing an interface for the system to alert the crew of warnings, violations, and subsequent actions taken by the onboard system. Additionally, the LDU provides an interface for the crew to acknowledge authorities and alerts provided by the dispatching system and V–PTC server.
- The V–PTC Onboard System is physically attached to the locomotive that it monitors and reports on. The physical onboard system (Figure 3) is comprised of the following:
  - GPS System
  - Locomotive Sensor Suite
  - Brake Interface Unit (BIU)
  - Onboard Display Unit
  - Onboard Audio Unit
  - LCU, LDU, LDS

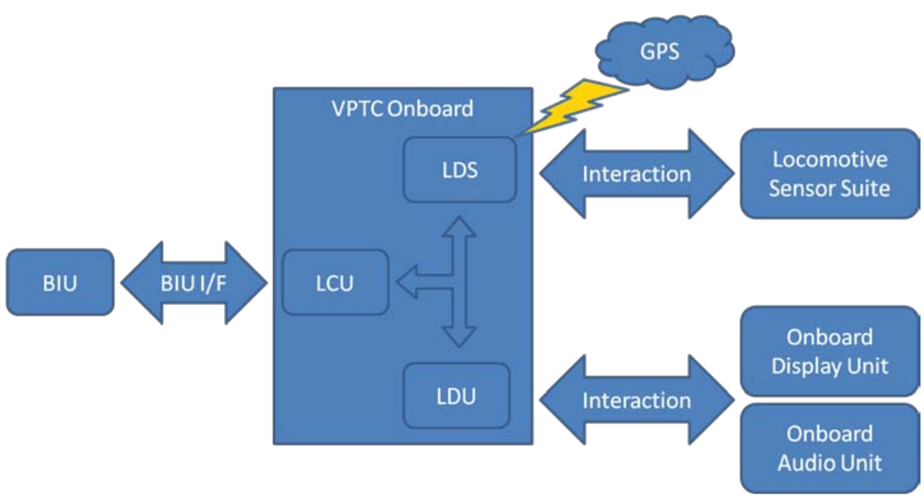

Figure 3. Physical Interaction Diagram

2.3.1 LCU

The major functionality that the LCU is responsible for performing is as follows:

- Locomotive Health Monitoring and Reporting

- Locomotive Location Reporting
- Locomotive Consist Management
- Locomotive Authority Enforcement
- Locomotive Speed Enforcement
- Locomotive Route Enforcement
- Locomotive Data Logging

The LCU is responsible for integrating and maintaining the state of the various components of the locomotive, including the other V–PTC onboard subcomponents, as well as the overall state of the locomotive. As a part of the overall state of the locomotive, the LCU periodically checks its internal health and ability to stop the train as necessary. This interaction requires that the LCU interface with the BIU and periodically check to ensure that the BIU is functioning correctly. Additionally, the LCU is responsible for reporting locomotive location and state to the V–PTC Server, which in turn reports the information to the system operator and dispatch system.

The various states that the LCU can assume are as follows:

- Powered Off
- Powered On
- Offline
- Initialized
- Enabled
- Operational

Each of these states and state transitions are determined by the LCU and communicated to the other onboard components and the V–PTC Server. The Powered Off state is the initial PTC state for the locomotive, when the LCU has been turned off, and the brakes are subsequently applied to the locomotive. When the LCU is turned on, the V–PTC Onboard system moves into the Powered-On state. In this state, the Power-On-Self-Test procedure is executed along with Initial Program Load. After this, the V–PTC Onboard software is successfully loaded onto the various processors and the system transitions into the Initialized state.

This state has two substates, Departure Test Required and Departure Test Complete. After completing Departure test and initializing the train, the V–PTC onboard system transitions from the Initialized state into either the Enabled state or Operational state depending on whether the locomotive has mapped to controlled track or not. If the locomotive has mapped to controlled track, the system is deemed operational, and the V–PTC Onboard system proceeds to enforce the train as appropriate.

The only substate that could occur while the locomotive is in the Operational state is the Out of Communications substate. The Out of Communications substate is entered whenever the locomotive loses communications with the V–PTC Server. After the locomotive has accomplished its route and loses all authorities it has, the V–PTC Onboard system can transition back to the Initialized state in the Departure Test Complete substate. Figure 4 illustrates the various states that the locomotive will transition through and the nominal flow of the V–PTC Onboard System. If at any time the LCU system detects a safety-critical fault in the software, it enters the Offline state, which requires a power cycle and possible maintenance to enable the train again.

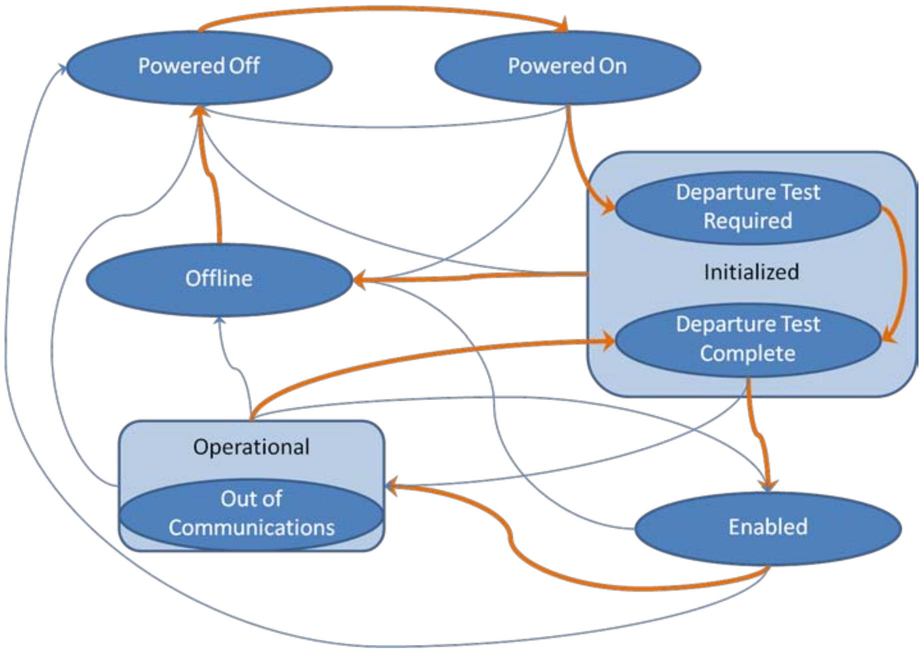

Figure 4. Locomotive State Diagram

The LCU is additionally responsible for ensuring that its datasets (Consist, Authority, Bulletin, and Track Database) are internally consistent. Each of these datasets is periodically checked to ensure that the data has not changed without the proper authorization. Each dataset is safeguarded through the use of Cyclical Redundancy Checks (CRCs), which are also periodically checked against the V–PTC Server CRCs to ensure that the onboard data is the same as the data the V–PTC Server has stored for the locomotive.

All of the datasets are used for enforcement purposes to ensure the locomotive follows the railway operating procedures and the authorities granted it by the dispatching system. Consist data is used to determine the train characteristics, and it is used to determine braking points and maximum speed constraints for the whole train. Authority data is used to determine what routes the train has permission to traverse and at what points the train is required to stop. Speed data and bulletin data are used to enforce speed restrictions as set up by the dispatch system.

Finally, the track database is used to determine track characteristics, including gradient, curves, and maximum speed limits at certain locations along the track. Additionally, the track database contains switch locations, which are used to determine monitored switch locations as well as unmonitored switch locations for the purposes of enforcement and to ensure the train is moving correctly over the switch.

As the LCU controls the interface over the BIU, the LCU is responsible for determining when enforcement occurs, whether due to speed violations or authority violations, and reporting this information to the V–PTC Server.

The system is required to be fail-safe and ensure correct communications and operations; therefore, the eventual architecture will have multiple components performing all LCU operations in parallel. These multiple components will need to ensure their communications and actions taken are in sync to ensure correct operation of the locomotive.

2.3.2 LDS

The LDS system determines the location of the train and serves as the main interface for all the train sensors. The LDS is connected to the onboard GPS antenna and uses the GPS system to determine initial locomotive location. If the LDS is unable to map to track in multiple track territory, it is responsible for requesting crew input to determine which track the train is currently occupying. Once the train is mapped to track, the LDS uses inertial navigation to determine higher levels of accuracy in location reporting.

As the main onboard interface with the locomotive sensors, the LDS is responsible for reporting to the other components train and locomotive data including location, speed, direction, brake pipe pressure, and status of the various components of the train.

2.3.3 LDU

The LDU system is responsible for providing audio and visual interface with the locomotive crew members. At the direction of the LCU, it provides various alerts and warnings to the crew members to notify them of impending or current actions taken to ensure the train operates in accordance to the authorities and speed restrictions given to it. To provide the alerts and warnings, the LDU uses the Onboard Display Unit and associated audio devices to notify and alert the crew as necessary.

2.4 Communication

Communication between the V–PTC Onboard system and the V–PTC Server is expected to occur over one of multiple potential communication media, e.g., satellite link, cell phone data packets, radio packets, or wireless Internet. The V–PTC Onboard system and the V–PTC Server will determine which of these media to utilize at any given time based on availability and priority.

Although the LCU is the only onboard component responsible for communication with the V–PTC Server, at any one time due to safety and reliability constraints, the LCU may be comprised of multiple smaller subcomponents, each able to communicate with the V–PTC Server. To eliminate competition between the various subcomponents, the LCU ensures that only one subcomponent is communicating with the V–PTC Server at any given time. Likewise, a similar scheme is utilized to ensure that only one element within the LCU is communicating with the LDU at any given time.

3. V–PTC System Development

To comply with V–PTC technical advisory group and FRA guidance, the project was implemented using an approach based on providing demonstrated incremental progress during the system development cycle. V–PTC functionality development and related testing were distributed throughout eight phased builds. These builds were organized into five groups of demonstrated and deployable capability. Figure 5 shows an overview of the system build cycles.

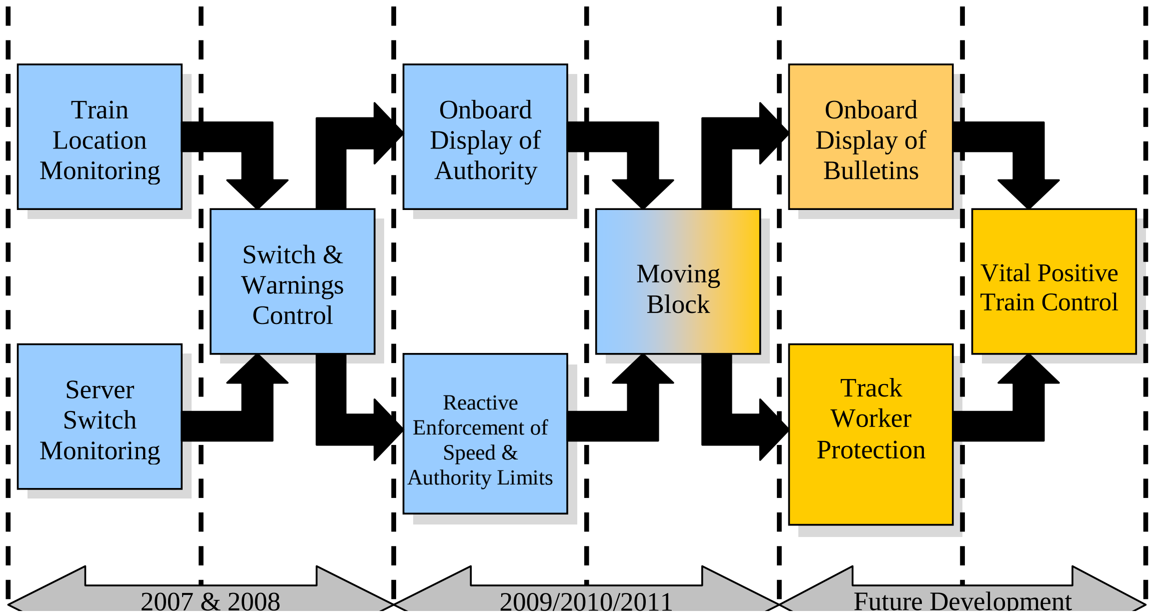

Figure 5. V-PTC System Build Cycle Overview

3.1 Build 1—Train Location Monitoring

Build 1 was designed to provide the functionality of determining the accurate location and speed of a train without the aid of track circuits and report these data to the V–PTC Server. The objectives of Build 1 were to:

- Demonstrate Onboard Train-Borne Navigation Performance during field testing at TTC
- Train Location Position Accuracy
- Train Velocity Measurement Accuracy
- Route Determination
- Demonstrate V–PTC Server Build 1 Capabilities
- Log-On Password
- Time Alignment
- Message Logging
- Message Receipt Status
- Software Version Reporting
- Demonstrate that an effective radio link can be established and maintained between train-borne equipment and the V–PTC server at the TTC facility

3.2 Build 2—Server Switch Monitoring

Build 2 was designed to develop the V–PTC capability to monitor and report the alignment of both powered and nonpowered (hand-operated) switches, the status of associated on station track circuits, and to ensure that all of these conditions are reported to the V–PTC Server.

3.3 Build 3—Switch Warnings and Control

The purpose of Build 3 was to ensure that all of the data in the previous builds, including switch point position, is transmitted to the onboard display of the locomotive and that the data can be seen and evaluated by the locomotive engineer in the cab of the locomotive. The objectives of Build 3 were to:

- Demonstrate switch awareness capability by the V–PTC Server
- Display correct train location on mapped track
- Display configuration and location of track features (switches, crossings, mileposts, etc.) within the horizon
- Display train speed and current time onboard the locomotive
- Display results of onboard train-borne power up integrity checks
- Display status of onboard train-borne health monitoring processing
- Demonstrate V–PTC BOS to wayside or train-borne unit communications over the PTC Test Bed's communications network using MeteorComm MCC-6100 radios
- Respond to a V–PTC technical advisory group request from Build 1 testing to demonstrate a 40-mile per hour turnout through Switch 301 of the RTT
- Verify that the display of train location and track features is correct
- Perform turnouts using both short-hood forward and long-hood forward configurations

3.4 Build 4—Onboard Display of Authority

Generally, Build 4 was intended to (1) verify the capability to remotely control alignments of monitored and powered switches by a dispatcher using the CAD/BOS interface, (2) transmit the information monitored in Builds 1 and 2 from the V–PTC BOS to the CAD system using the interface, and (3) display all authorities entered by the dispatcher to the locomotive engineer in the cab of the locomotive. Build 4 capabilities were implemented in two parts, 4A and 4B. The specific objectives of Builds 4A and 4B are described below.

3.4.1 Build 4A—Specific Objectives

- The V–PTC Server will receive requests to set nonsignaled control points from the dispatching system. The V–PTC Server will command the WIU to set the power operated switch in the requested position after verifying the request is safe to grant.
- The V–PTC system will align a power operated switch at a nonsignaled control point consistent with requests from the dispatching system when none of the following conditions apply:
  - The switch is occupied.
  - The switch is in local control.
- The V–PTC system will reject a dispatching system request to align a power operated switch at a nonsignaled control point when any of the following conditions apply:

- The switch is occupied.
- The control point is in local control.

- The V–PTC system will prevent the operation of a power operated switch at a nonsignaled control point when it is occupied by a train.

3.4.2 Build 4B—Specific Objectives

- Monitor powered and hand switches at the dispatch system
- Prevent the operation of a power operated switch at a nonsignaled control point when it is occupied by a train (normal, reverse, and unknown switch positions)
- Control powered switches remotely from the dispatch system
  - Normal operations mode (normal and reverse moves)
  - Overswitch protection
  - Local Control Mode (LCM)
  - Switch change request rejections
- Monitor powered and hand switches at the dispatch system
- Verify train location monitoring at the dispatch system
- Verify correct operations of the V–PTC Server under different test conditions including communication outages
- Verify train-borne displays the switch states in the display horizon

3.5 Builds 5–8—Reactive Enforcement of Speed and Authority Limits

Builds 5–8 encompassed system capabilities associated with movement authorities and related functionalities. Builds 5–8 were developed as a coordinated group and then tested in a single on-track test period November and December 2009. The general capabilities developed during these builds included the following:

- Verification of train location monitoring at the dispatch system
- Initialization and synchronization of V–PTC Server, RailComm CAD, and Onboard V–PTC system components
- Awareness and remote control of switches
- Location determination and display on the CAD system
- Health status monitoring of the V–PTC Server and Onboard systems
- Train activation
- Issuance, delivery, and management of authorities
  - Proceed authorities
  - Cancel and reissue of proceed authorities
  - GCOR Line 9 conditional authorities
  - Cancellation of proceed authorities
  - Route integrity monitoring
    - Stops and inspections
    - Route locking
  - Enforcement actions for speed and authority violations
  - Train termination

3.5.1 Builds 9+

After the completion of field testing and movement authority roll-up demonstrations at the end of the Builds 5–8 development cycle, LMC had met its project funding obligation to provide a total of $6 million over three years. Nonetheless, LMC and the V–PTC technical advisory group desired to continue V–PTC system development. For continuation efforts, the initial plan was to continue the incremental development cycle until the system had moving block functionality, which was actually implemented as virtual block instead. However, in response to available project funding (for both FRA and LMC), the project emphasis shifted to developing and demonstrating the LMC implementation of the TTCI-developed PTC EBA and to revising the SRS for Builds 5–8 to include the remaining functionalities needed to provide V–PTC virtual block capabilities. The principal additional SRS functionalities included:

- Roadway Worker Protection
- Temporary Speed Restrictions
- Advance Grade Crossing Activation
- Virtual Block-based Movement Authorities

These points of emphasis were completed during the fourth quarter of 2010.

4. Enforcement Braking Algorithm Evaluation

As part of the V–PTC project's focus on addressing PTC related issues, the V–PTC technical advisory group asked the TTCI team to examine some of the effects of PTC EBA on freight train operations. During pilot operational use of other PTC systems, train crews had experienced penalty brake enforcements in situations for which they were not warranted. For example, as the crew slowed a train while approaching a stop, the train too often received a PTC penalty brake enforcement that stopped the train short of the intended stopping position. Several operational conditions appeared to have caused these issues, primarily braking operations for which dynamic and/or independent braking is typically used:

- Slow speed operations—less than 20 mph, typically less than 15 mph (this issue was catalyst for V–PTC EBA efforts)
- Short train operations—trains for which the locomotive weight is dominant
- Steep downgrades—where dynamic brake use is required, but is not accounted for in EBA in use at the time

One observation early in the EBA evaluation process was that the use of dynamic braking was not accounted for in algorithms used at the time. Normal crew braking procedures are to use dynamic braking to slow the train to ~5 mph, then use a combination of automatic and/or independent braking for speeds below 5 mph, when dynamic braking becomes ineffective. However, predictive EBA used at the time were based solely on the use of automatic braking (i.e., assumed no use of dynamic or locomotive independent brake). Additionally, in order to achieve a very high level of safety assurance, the predictive EBAs used at the time also made the assumption that the train exhibits worst-case braking system parameters. Consequently, the algorithms in use at the time were so conservative that penalty enforcement was initiated earlier than necessary and stopped trains significantly short of their target stopping locations.

As part of the EBA evaluation efforts, the operational conditions described above were examined by running simulations using TOES, a validated, widely accepted model for simulating freight train performance in detail. For each operational condition, simulations were run to compare where a train crew would typically begin stopping the train to where a conservative enforcement algorithm would initiate a penalty brake application. To model where the enforcement algorithm would initiate a penalty application, simulations were run that incorporated worst-case braking system parameters, including:

- ABD type control valves
- Long brake cylinder piston stroke
- 8.5 percent net brake ratio
- Loads with 10 percent overweight

To model where a train crew would typically begin stopping the train, simulations were run using braking procedures defined in BNSF Railway Company locomotive engineer training material. These simulations incorporated "nominal" braking system parameters, including:

- ABDW type control valves
- Nominal brake cylinder piston stroke
- 10 percent net brake ratio

- Nominal rated loads

In addition to simulating where a conservative enforcement algorithm would initiate a penalty brake application, a number of other potential enforcement strategies were identified and simulated. A total of eight simulation cases were run for each operational condition. Seven of the eight cases represent the various braking strategies, and a target case represents how a train crew would operate the train to a stop. The eight cases are:

- **Case 1—**Full service brake enforcement to train stop that assumes independent brakes are bailed (typical conservative enforcement algorithm assumptions)
- **Case 2—**Full service brake enforcement to train stop that precludes bailing of independent brakes
- **Case 3—**Full service brake enforcement to 26 psi brake pipe pressure reduction, precluding bailing of independent brakes
- **Case 4—**Case 1 with emergency brake backup (after penalty is through train)
- **Case 5—**Case 2 with emergency brake backup (after penalty is through train)
- **Case 6—**Case 3 with emergency brake backup (after penalty is through train)
- **Case 7—**Emergency brake enforcement to train stop
- **Target Case—**Normal train crew braking procedures (combination of dynamic, independent, and automatic brakes used)

Figure 6 shows the results of these simulations for a 100-car loaded general freight train running at 10 mph. The figure shows where enforcement would occur for each of the eight cases, in order to stop the train at the same location as the target case. It also shows where a 20-second and 40-second warning would occur for Case 1. The figure illustrates the observed issue that warnings and enforcements occur before a train crew would begin to bring the train to a stop using normal operating procedures. The figure also illustrates that use of the independent brake and/or use of the emergency brake as a backup for a worst-case train could help reduce the negative operational effect of the conservative nature of the EBA.

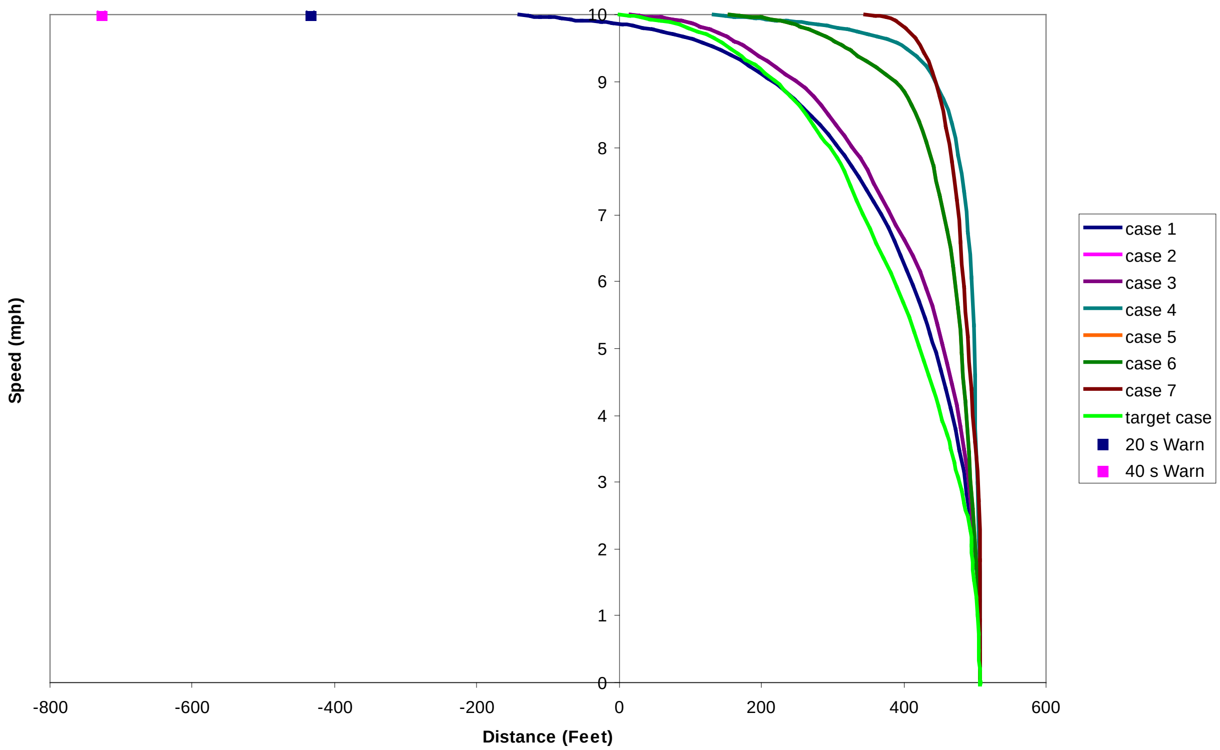

Figure 6. Braking Distances for Slow Speed Operation

Figure 7 shows the results of these simulations for a short train operational scenario. The train consist for these simulations included 10 loaded general freight cars, and the simulations ran at an operating speed of 40 mph. In this case, the effect of bailing the independent brakes results in a much longer stopping distance in case 1 than in the target case. This has a similar effect as the slow speed operation of warnings and enforcements occurring before the train crew would normally begin stopping the train. Use of the independent brake in these cases has a dramatic effect on the stopping distance, and results in the enforcement occurring after the train crew would normally begin to stop the train.

Finally, Figure 8 shows the results of these simulations for an operating scenario with a steep downgrade. In this case, the 100-car loaded general freight train was operated on a -2 percent grade at 20 mph. In this case, dynamic brakes were used to control the speed of the train before enforcement. However, because of the EBA's assumption that dynamic brakes are not used, the train begins to accelerate following the point of enforcement, until the air brakes have time to propagate through the train. This assumption results in a dramatically longer stopping distance for case 1 than for the target case, which assumes that dynamic brakes will be used to help stop the train. Again, it results in warnings and enforcements before the crew would normally begin the braking process. As with the previous operational conditions, use of the independent brake and emergency brake as a backup has the potential to reduce the negative operational impact.

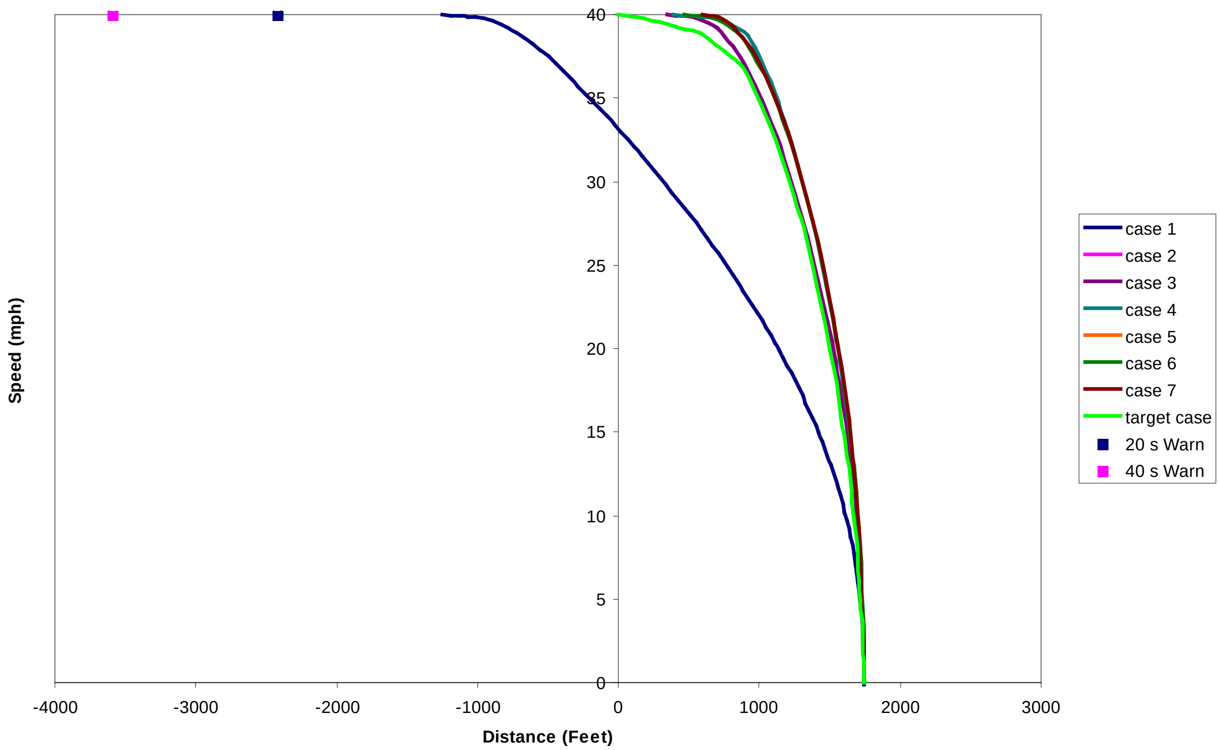

Figure 7. Braking Distances for Short Train Operation

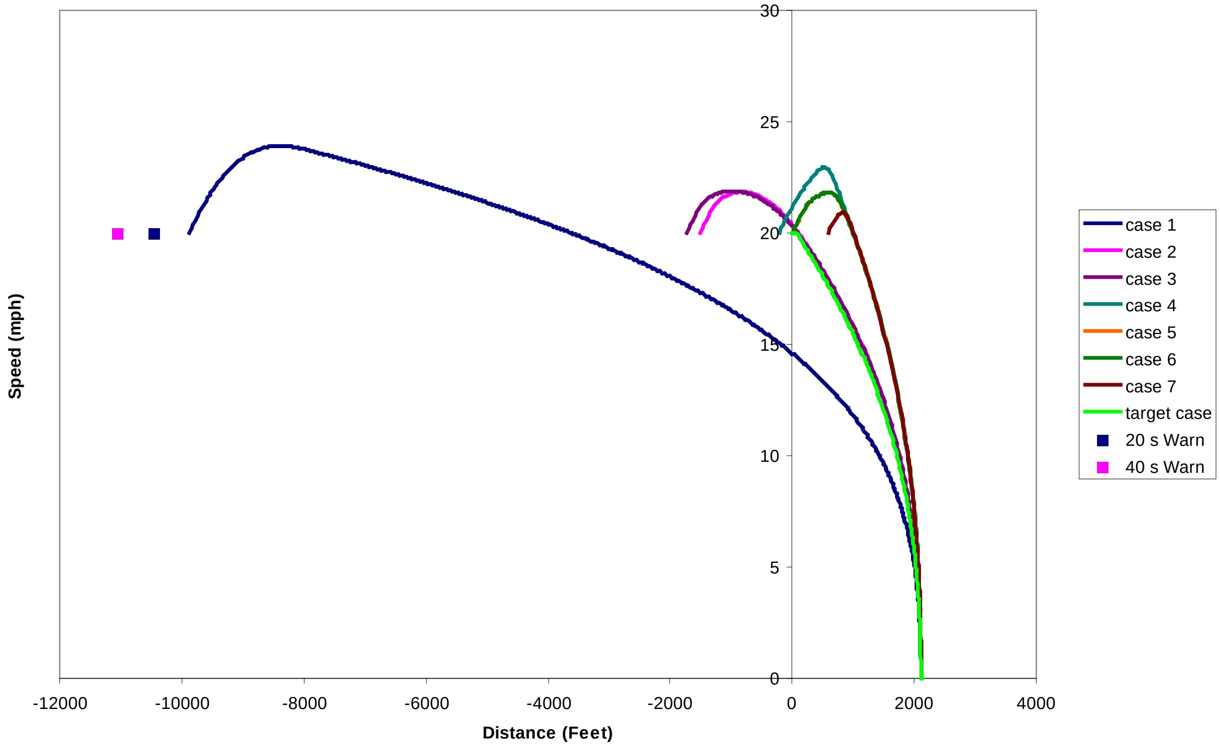

Figure 8. Braking Distances for Steep Decline Operation

The analysis of the effect of PTC EBA on freight train operations demonstrates, through simulation test results, that a PTC enforcement algorithm that assumes worst-case braking characteristics, no use of independent brake, and no use of dynamic brake has the potential to have a significant negative impact on freight railroad operations. The analysis also shows the potential improvement by including independent and emergency braking as part of the PTC enforcement solution. Additionally, an algorithm that has the ability to adapt to the braking characteristics of a specific train to alleviate the conservatism of assuming worst-case braking characteristics has the potential to further reduce the negative operational impact. As a result of this analysis performed as part of the V–PTC project, a separate project to further investigate methods for improving PTC enforcement algorithms was initiated.

5. TTC's PTC Test Bed

As part of the incremental development approach, V–PTC system performance was evaluated at the end of each major build cycle. On-track testing was conducted at TTC using the PTC Test Bed developed by TTCI with FRA support. The Test Bed was initially developed and subsequently upgraded to provide an industry resource for testing PTC-related systems, equipment, and technologies in an environment free of the requirements associated with revenue service test activities. Compliance with requirements associated with testing on revenue service routes can present testers with significant challenges. Examples include:

- Must schedule test activities around revenue service traffic
- Must obey all operating rules or obtain waivers (frequently a lengthy process)
- Difficult to conduct stress testing (i.e., degraded equipment or high capacity performance testing)
- Test conditions (and, therefore, test results) are often not repeatable
- Changes to vital equipment require lengthy verification and validation processes before retest is possible

Among other uses, the PTC Test Bed provides a facility that can be used for supporting development of PTC systems, for conducting performance evaluations of PTC system segments, and for performing interoperability and compliance testing. PTC system development could include proof of concept demonstrations, system development testing, and simulations and on-track (field) tests. Performance evaluations would likely involve (1) Locomotive onboard equipment, (2) Communications infrastructure components, (3) BOS and CAD/BOS interfaces, and (4) WIU (for trackside systems). Interoperability and compliance testing could be for initial equipment acceptance and for interchange operations.

Examples of potential PTC Test Bed uses include the following:

- Preliminary field trials and debugging of PTC systems
- Development and testing of improved PTC braking algorithms
- Evaluating impact of communications system performance and loading on PTC system performance
- Development and test of PTC positive end of train determination
- Preliminary field testing of an Employee in Charge Portable Remote Terminal
- Demonstrating operation of PTC highway crossing protection systems
- Certification/acceptance testing of PTC systems or components
- Interoperability/interchange testing of multiple PTC systems

The V–PTC project facilitated certain upgrades to the test bed and provided extensive opportunities over several years to debug and validate the PTC Test Bed.

5.1 PTC Test Bed Overview

The PTC Test Bed consists of railroad track infrastructure, communication infrastructure, PTC equipment, railroad vehicles/rolling stock, laboratories, and specialized software (instrumentation and modeling) tools that provide the capabilities to perform consistent and realistic test environments for PTC systems and railroad communication systems. The elements of the PTC Test Bed are building blocks that can be assembled in multiple configurations to provide a desired test environment or scenario. The PTC Test Bed at TTC provides an independent, dedicated, and controlled test environment that does not interfere with the productivity of railroad revenue service operations. It allows PTC testing to be conducted very efficiently without interference from revenue trains.

5.2 PTC Test Bed Elements

The PTC Test Bed is composed of numerous elements that can be configured to establish test environments needed to conduct evaluation of PTC systems and components. The test bed elements fall into three classes:

Fixed Test Bed Elements: These are features of TTC's test facilities that can be incorporated into test environments, but cannot, in general, be altered significantly from their initial state. Fixed test bed elements are full-scale equipment and facilities located at TTC and include:

- RTT
- Transit Test Track (TTT)
- Sidings, turnouts, crossing protection systems, and other railroad infrastructure
- Locomotives and rolling stock

Quasi-Fixed Test Bed Elements: These are features of TTC's test facilities that are typically incorporated into test environments as is, but can be altered if necessary and generally require more effort to do so than for configurable elements. Quasi-fixed test bed elements are full-scale equipment and facilities located at TTC. These elements include:

- RF communication infrastructure
- PTC WIUs
- PTC locomotive equipment
- PTC BOS
- CAD systems
- Signal systems, such as the GE Electrified ElectroCode-4+ system on the RTT
- Backhaul/data network

Configurable Test Bed Elements: These are features or components of the PTC Test Bed that can be readily altered, modified, or scaled as needed to create a test environment. Configurable test bed elements are modular and in many cases are used to overcome or mitigate limitations of fixed or quasi-fixed elements. Configurable test bed elements include:

- Rail Traffic Controller (RTC) Model and Post Processor
- Train Simulator
- WIU Simulators
- Network Traffic Generators

In addition to the fixed and configurable elements, the PTC Test Bed includes test support elements. Test support elements are equipment and software tools needed to collect data, analyze data, or augment the characteristics of the test environment. These elements include:

- Data collection
- Track database

- Test Software Environment Controller
- Automated test script generators/Test Designer
- Test Equipment (Spectrum/Network Analyzers, oscilloscopes, RF Noise Generator, and RF Channel Simulator)

5.2.1 Fixed Test Bed Elements

Railroad Test Track

The RTT is a 13.5-mile loop with four 50-minute curves and a single 1-degree, 15-minute reverse curve. It accommodates maximum speeds of 165 mph. The RTT also has a 4,000-foot siding and a crossover to the TTT.

The RTT has three powered switches with on station circuits located at Switch 302, Switch 305 (each end of the 4,000 ft siding) and at Switch 602B (crossover to TTT). The RTT is divided into 12 signal blocks and is equipped with a GE Electrified ElectriCode 4+ (EEC 4+) signal system capable of supporting 9-aspect cab signaling. A 4,000-foot siding and a crossover to the TTT to allow for the execution of multitrain meet and pass type operational scenarios.

Transit Test Track

The TTT is a 9.1-mile oval track, equipped with a third rail power system and is used for vehicle performance and specification compliance testing. Vehicle performance investigations at speeds up to 80 mph are conducted. The third rail direct current (DC) electrified power system can provide transit and commuter vehicles with a variable of 0 to 1,000 volts of DC with a 3,500 ampere continuous rating. The track includes 3,333 yards of overhead DC contact wire catenary, suitable for low-speed operation and evaluation of light rail urban vehicles. The TTT runs parallel with the RTT for a significant portion of its overall length, allowing for the ability to conduct multitrack PTC scenarios.

Test Bed Communications Infrastructure

The following RF communication infrastructure is in place at TTC:

- 180-foot tower with collocated communication bungalow and power. Antennas for 160 MHz voice radio, 900 MHz data radio, 450 MHz vehicle tracking system, and 11 gigahertz microwave T1 are installed. Antennas for communication systems under test may be placed on this tower at heights specific to the RF coverage footprint needed.
- 120-foot tower with collocated communication bungalow and power. Antennas for 160 MHz voice radio and 900 MHz data radio channels are installed. Antennas for communication systems under test may be placed on this tower at heights specific to the RF coverage footprint needed.
- Three 802.11 b/g access points with antenna heights ranging from 40 to 100 ft that provide on-track sites for wireless data download points.
- CDMA cellular (Verizon) tower and service

Figure 9 shows locations of communication towers and RF infrastructure at TTC.

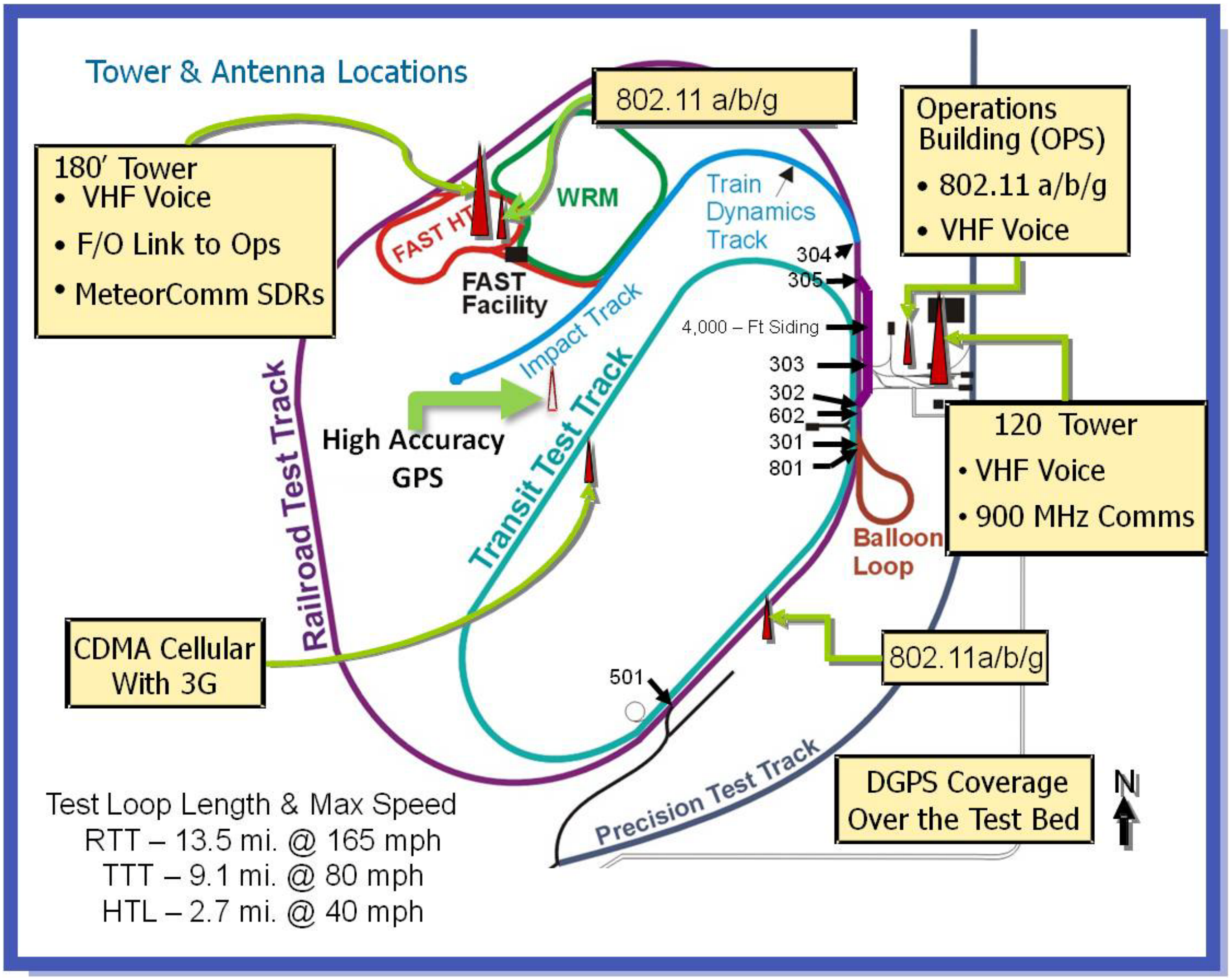

Figure 9. Track and RF Communications Infrastructure

Backhaul infrastructure for the RF communications infrastructure and PTC field networks is provided by data networks that are segregated from the TTCI business data network. The isolated backhaul infrastructure allows for testing of communication equipment that is unperturbed by data traffic generated by TTCI's business applications. Figure 10 provides an overview of the network infrastructure in place at TTC to support test of communication and train control systems.

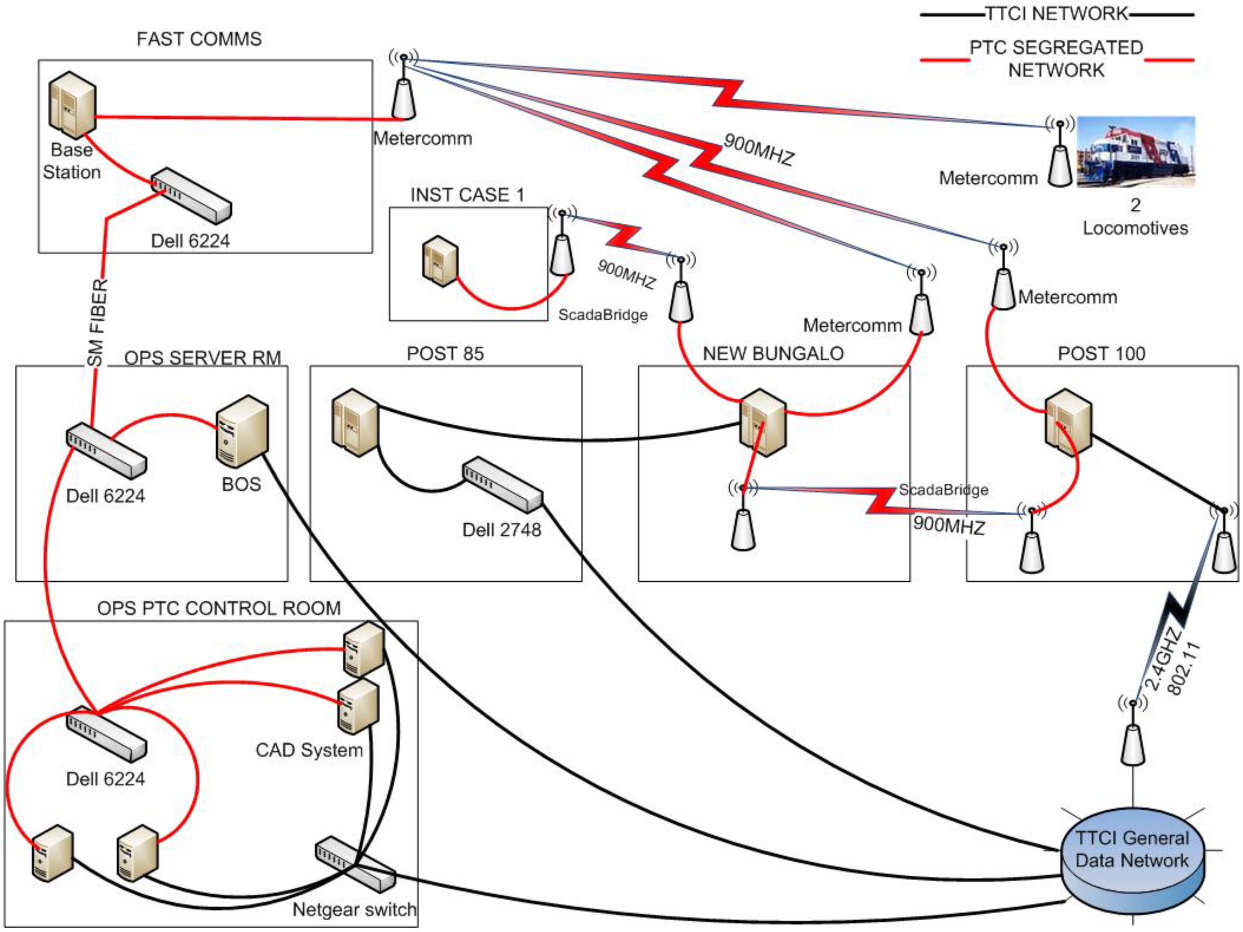

Figure 10. Backhaul and Data Network Overview

Train Control Infrastructure/PTC Equipment

The PTC Test Bed is currently configured for supporting on-track development testing of the V-PTC system. To support testing of this PTC system with an office-centric architecture, the current PTC Test Bed configuration includes the following items:

- One CAD system with an interface to a BOS
- One BOS optimized for the V–PTC system
- Four PTC control points in the form of remotely monitored and controlled powered switches
- Three locomotives equipped with PTC locomotive segment equipment (from V–PTC)
- Three WIUs comprised of Ansaldo STS MicroLok II object controllers
- Six MeteorComm MCC 6100 software definable radios (SDRs) used for PTC communications between WIUs, locomotives, and a base station
- One GPS-based track database for the RTT and other selected track segments

The PTC Test Bed is in the process of being upgraded so that additional PTC testing configurations can be supported. When the upgrades are completed (end of first quarter 2011), the following features will have been added to the PTC Test Bed:

- A Wabtec Train Management and Dispatch (TMDS™) CAD system and V/ETMS®* BOS
- Two locomotives equipped with Wabtec V/ETMS onboard systems
- Six 12,000-foot (~2¼-mile) signal blocks with 4-aspect block signaling that is PTC capable
- GE WIUs for signal block and control point ITC-compliant communications
- Twelve MeteorComm MCC 6200 radios communicating at 220 MHz

* Note that when the term "V/ETMS" is used in this document, it refers collectively to the V-ETMS® PTC system and the ETMS® PTC system, both of which are registered trademarks of Wabtec Corporation.

Radio Laboratory Facilities

The radio laboratory at TTC (Figure 11) is equipped to support testing of individual radios or networks of radios. It can be operated as an independent facility for testing the performance and limitations of railroad data radios within a highly controlled and reproducible environment. The TTC radio laboratory features:

- Capability to support testing of radio networks of 50+ radios
- Low noise uninterruptable DC power
- Access to rooftop antennas for combination laboratory/field testing
- Access to GPS
- Stratum 1 time synchronization
- Noise and interference injection capabilities for evaluation of physical layer performance
- Link access protocol performance testing capabilities
- Network infrastructure isolated from TTCI business network
- Remote test monitoring and data acquisition

Figure 11. Radio Laboratory at TTC

5.2.2 Configurable Test Bed Elements

Train Simulator

The Train Simulator software component is used to mimic the operation of either a PTC or non PTC-equipped train operating over real or simulated PTC territory. It allows simultaneous operation of simulated trains and real trains on the test bed track. It is comprised of a train motion simulator, PTC logic implementation, and several data communications interfaces. The Train Simulator is used to provide realistic simulated train movements within the test scenario and to generate the appropriate PTC messages to accompany that train motion. In addition, the Train Simulator can be configured to generate exception conditions, such as undesired emergencies, communications equipment failures, logical PTC messaging failures, and the failure to the train crew to respond to PTC messages appropriately. The Train Simulator is designed to be used to model theoretical as well as realistic PTC usage scenarios over PTC-equipped territory, non PTC-equipped territory, or even nonexistent territory to explore the likely or possible operational characteristics of the PTC system under test during normal and abnormal operating situations.

The Train Simulator communicates with the Environment Controller, the data collection system, and the simulation definition database. The Environment Controller provides remote configuration, control, and monitoring functionality. The data collection system provides the ability to log operational parameters for later analysis. The simulation database provides data to the Train Simulator, which defines the characteristics of the train being simulated, the territory over which that train operates, and the operational rules for operating that train (speed limits, authority boundaries, operational movements, etc.).

Both the PTC implementation logic and the data communications interface are implemented in a way that allows them to be configured or developed to quickly alter the PTC operation of the train simulator. This allows for comparative analysis of several PTC systems using a specific data communications infrastructure, or for comparison of various PTC implementations over a single data communications infrastructure.

The Train Simulator is intended to replace or supplement the use of PTC equipped trains within the PTC Test Bed. There are a number of reasons for this. Primarily, it allows for testing scenarios that are deemed to be unsafe using only physical equipment. For instance, it might be desirable to test PTC enforcement with a case where multiple trains are operating in close proximity on the RTT. However, this would be in contravention to the operating and safety rules in place at TTC. Therefore, the number of trains that are seen to be operating on the track by the PTC implementation could be augmented safely and/or more cost-effectively by using the Train Simulator.

In addition, the Train Simulator can be used as part of a test of PTC operation over track that either does not exist or is not currently equipped for PTC operation. In this case, the Train Simulator provides the ability to conduct “what if” testing in advance of actually installing PTC hardware and testing the boundary conditions of a particular PTC implementation safely.

Finally, the Train Simulator provides a low cost alternative for doing comparative analyses of either PTC implementations or data communications infrastructures. Due to the modular nature of the software, either the PTC logic or the data communications interface can be replaced much more easily and cost-effectively. It is possible to test different PTC implementations using the same data communications equipment over a given territory or different communications infrastructures using the same PTC implementation over the same territory. It allows for a form of implementation optimization before costly hardware and software is sourced.

Network Traffic Generator

The Network Traffic Generator software component is designed as a tool to generate message traffic across many different data communications networks. It can be used as either a tool to provide simplified network traffic flow for capacity analysis or to generate network "background message traffic" during a more detailed testing scenario.

When used to provide capacity analysis, the Network Traffic Generator can be configured to send a number of independently controlled message profiles, which may send messages to any number of other instances of the Network Traffic Generator over any number of known and defined data network interfaces. Messages received from other instances can also be used as triggering mechanisms to initiate message transmission (message spawning). In this mode, the message transmission and reception times are logged into the data collection system to allow for later analysis of metrics such as message latency distributions and message loss rates.

As a background message traffic generation tool, the Network Traffic Generator is used to generate message traffic associated with systems outside of the PTC system under test, such as signaling and CAD systems or additional PTC nodes that are not physically present. In this scenario, the Network Traffic Generator is simply used as a tool to decrease the available data message throughput for the network under test. In this case, the message statistics may or may not be logged, depending upon their degree of usefulness in statistical analysis.

The message profiles within the Network Traffic Generator allow for the specification of message size, number of instances, priority, and distribution of message transmission times. Currently, message distributions may be defined as deterministic (e.g., scripted), uniform within a given time period, Gaussian, or Poisson. The message distributions may be altered as the test progresses. Also, the message distribution types can be expanded as additional needs are indentified.

When used in high-level capacity testing, the Network Traffic Generator is designed to replace any single component of a PTC System. In this mode, the purpose of the test is to analyze the data traffic flow within the system, without the need to implement all the details of the actual component. For instance, the Network Traffic Generator can be used to mimic the expected network communications traffic for a PTC office server, without the need to implement all the logic associated with the office server itself. This allows for quicker high level testing of data communications equipment tailored to the specific needs of a particular PTC implementation. The expected data message profiles are provided by an external tool, such as TTCI's RTC post-processor application, and then translated into a format suitable for the Network Traffic Generator. TTCI has implemented a translator for converting RTC post-processor output into the necessary input format for the message generators.

In the second intended mode of operation, the Network Traffic Generator is designed to replace non PTC communications equipment such as code line replacement devices, CAD system interfaces, and other data communications equipment that may reduce the network throughput available to the PTC System components under test. In this mode of operation, the Network

Traffic Generator is not strictly a component of the actual test; it is more of a support component used to generate a more realistic and accurate test environment.

WIU Simulator

The WIU Simulator mimics the operation of a control point, intermediate signal, or turnout WIU within a PTC implementation and also provides the functionality to integrate real and simulated trains within the Test Bed. The WIU Simulator includes functionality to interface with physical track circuits, train presence detection components, PTC communications logic, and the Environment Controller. The WIU simulator has three main modes of operation, which make use of a subset of the various components:

- Simulated trains operating within physical PTC territory with physical control points installed
- Real and/or simulated trains operating over physical PTC territory without physical control points installed
- Simulated trains operating within theoretical PTC territory

In the first scenario, the WIU simulator interfaces with the physical signaling hardware to show track occupancy for the simulated train as necessary. In the second scenario, the WIU simulator implements the PTC control logic to determine the correct control point state and monitors the physical track to determine whether a physical train exists within its defined track circuit boundaries, as well as receiving information regarding the location of simulated trains. In the final scenario, the WIU simulator receives information regarding the location of simulated trains and determines the state of the control point from that information alone.

The WIU simulator includes an interface to the Environment Controller for remote configuration, command, and control. In addition, the WIU simulator receives the location of all simulated trains from the Environment Controller.

The WIU Simulator is intended to be used to augment or replace physical WIUs within a PTC test scenario for a number of reasons. The following are some examples that demonstrate how the WIU may be used:

- High-density control point testing on the RTT. It may be desirable to construct a test scenario that includes more control points than the RTT can support without significant track work or that TTCI has the physical hardware for. In this case, the WIU simulator can be used to increase the number of control points without additional installation time or expense. The WIU simulator would use low cost train presence detection to determine whether there was a physical train within its boundaries. It would also use PTC control and communications logic to communicate with other components of the PTC implementation under test.
- Integration of simulated trains into the physical PTC Test Bed. When simulated trains are used in conjunction with physical trains and control points, there needs to be some way to simulate their presence to the installed control points. In this case, the WIU simulator would use computer controlled relays to interface with the existing control point circuitry to simulate occupancy for the simulated train.
- Purely simulated PTC territory. In this scenario, there are no physical control points or trains present during testing. The WIU simulator would be used in place of all physical control points and would need to interface with the other components of the PTC

implementation under test. This allows the Test Bed to be used to simulate PTC operations over territory that either does not exist or is not equipped with any PTC equipment.

RTC Model and Post-processor

TTCI has developed a unique system for simulating PTC operations in large scale railroad operating scenarios, particularly for use in determining communications loading and other requirements. Railroad operations are simulated using the nation's most widely used network simulator, RTC. A custom post-processor developed by TTCI accepts RTC output files and generates a traffic profile of all messages communicated over data links versus simulation periods of up to six weeks. Another TTCI software application imports these traffic profile files into the message traffic generators used for stimulating actual radios under test. Figure 12 depicts TTCI's overall simulation process.

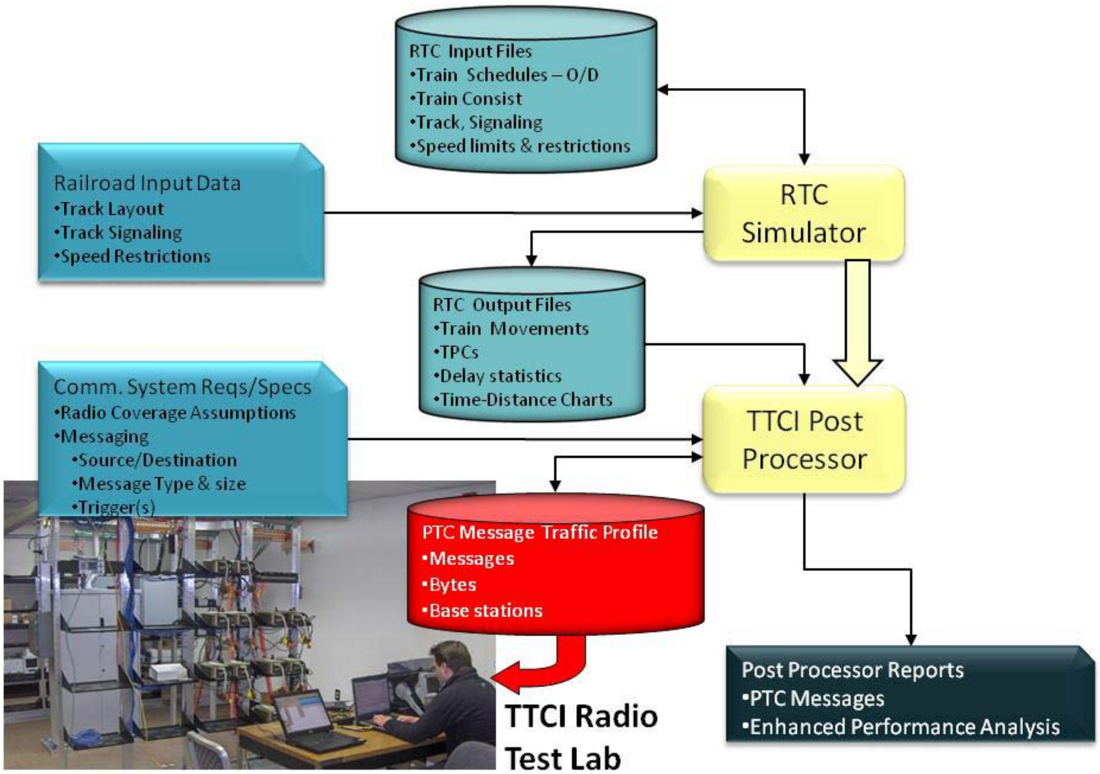

Figure 12. TTCI's Overall Simulation Process

5.2.3 Test Support Elements

Data Collection

The data collection and analysis system is used to store and analyze any and all data generated within the other PTC software components. The data collection system is implemented as an Oracle 9i database located on a dedicated server. Data may be collected either as testing is progressing or imported into the data collection after the test is completed using defined import routines and file formats.

The data analysis portion of the data collection system has been developed using the Microsoft.NET framework and is used to provide statistical analysis of the data collected during testing. The data analysis component is extensible and can be enhanced to meet the specific requirements of the testing of any particular PTC implementation or scenario.

Simulation Environment Database

The Simulation Environment Database contains the definition needed for any train and WIU simulators used for a particular test. This includes track definition, train and vehicle profiles, operating routes and rules, and the location and boundaries of any WIU simulators. The Simulation Environment Database is also implemented using Microsoft SQL Server and is located on a server connected to the Test Bed control network.

Test Software Environment Controller

The Test Software Environment Controller application has been developed to provide a central point to monitor and control each of the simulator instances used within a given test scenario. It is capable of distributing the configuration information to each software instance, coordinating the operation of each component and monitoring the status and health of each component.

The Test Software Environment Controller has been developed using the Microsoft .NET Framework and the C# language. It includes custom developed display and control components for each of the simulators within the Test Bed simulator suite. The number of software components that the Environment Controller can control is only limited by the available network and computer resources to the application. The Environment Controller application is installed on a dedicated computer connected to the Test Bed control network and is available for use both locally and remotely, allowing the progress of the test scenario to be monitored from any location that is able to connect through the TTCI corporate network.

Automated Test Script Generators/Test Designer

The Test Designer application has been developed to allow for the rapid design and configuration of testing scenarios. It has been developed using the Microsoft.NET framework and the C# language. The Test Designer includes a graphical user interface with typical Windows features such as drag and drop and copy and paste. It has been designed to allow the user to build up the configuration of test components without needing to understand the underlying test configuration file and database formats. In addition, the Test Designer includes the ability to import simulation data from an external application such as the RTC simulation model and post-processor. This data is then used as the basis for component configuration. This import facility is extensible, which allows for additional import routines to be developed and used based on customer or test scenario requirements. The Test Designer outputs scripting elements used by either the Environment Controller or the individual software simulation components.

5.3 PTC Test Bed Architecture

Figure 13 shows the PTC Test Bed architecture. The fixed and configurable test bed elements and the test support elements are connected by various communication networks. Locomotives and WIUs use RF communications links while all the configurable elements use local area network (LAN) connectivity. For the V–PTC system, the locomotives and WIUs use MeteorComm MCC6100 radios to send their data reports to the V–PTC BOS via the base station located in Communications Bungalow #1 in the Facility for Accelerated Service Testing area at TTC. In turn, the BOS relays appropriate data to the CAD system over a fiber optic LAN link. An interesting characteristic of this architecture is that communication interfaces directly with the BOS are via Ethernet. As a result, the BOS responds to data from simulated system components (simulated locomotives and WIUs) the same way it responds to "real" system components (actual locomotives and WIUs). Consequently, simulators can be used to increase the number of apparent units under test and determine a system's ability to handle higher capacity requirements. This approach significantly reduces the costs associated with PTC system capacity testing.

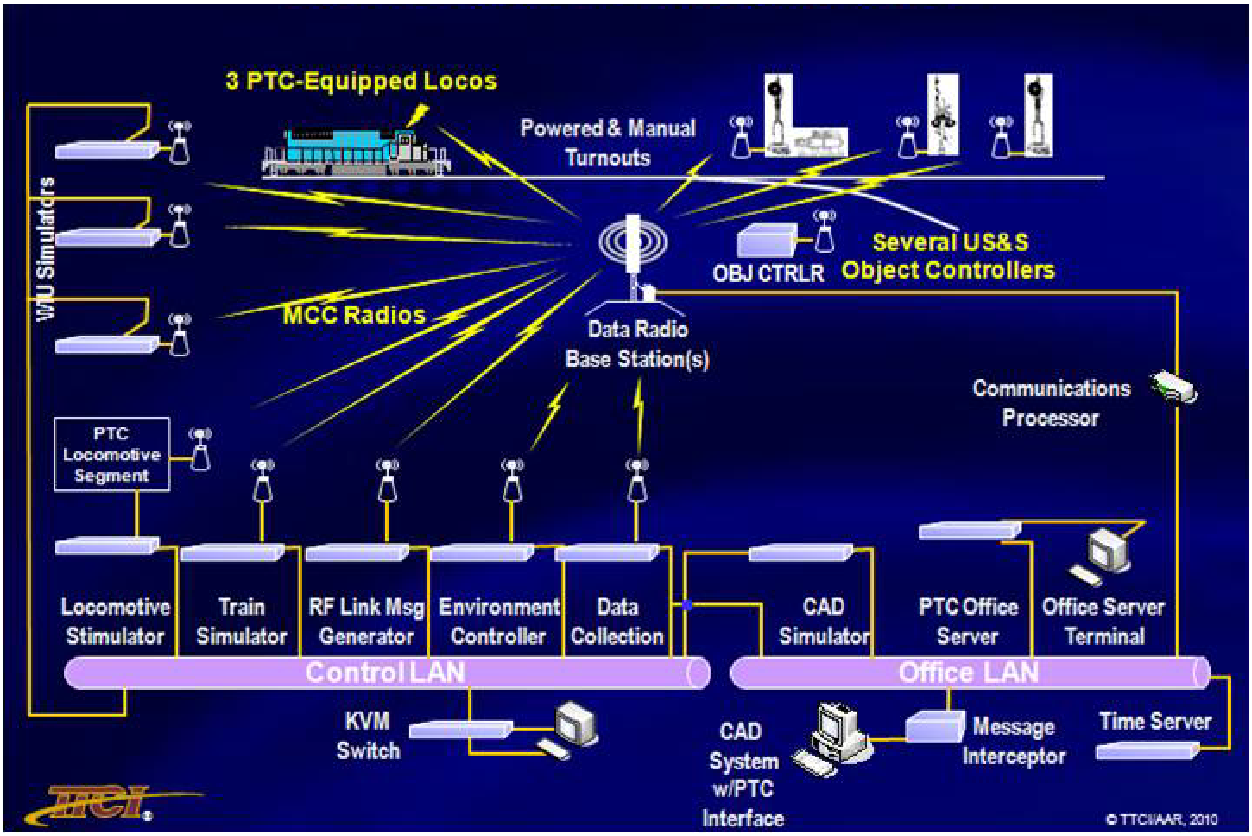

Figure 13. PTC Test Bed Architecture

5.4 2009 PTC Test Bed Upgrades

In 2008, it was determined that a siding on the RTT was needed to support V–PTC meet-and-pass testing and for other TTC test support purposes. A siding was installed in TTC's core area between Post 85 and Post 100 (see Figure 9). The siding and its associated equipment (powered switches, track signal circuits, relays, etc.) were installed in 2009. Figure 14 shows the relative positions of the siding turnouts and the locations of dwarf signal lights, which are used as switch point indicator lights. .

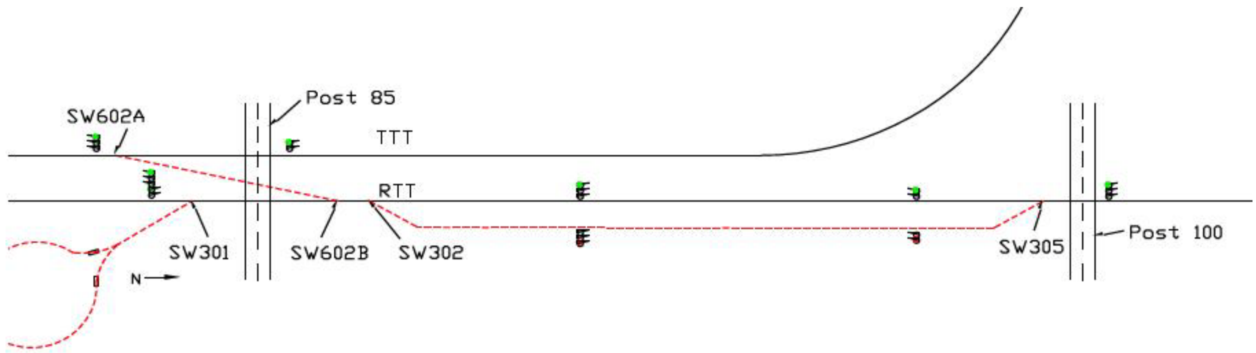

Figure 14. Siding Turnout Positions

At each end of the siding, a powered switch was installed with its controls located in an adjacent bungalow. Also, both hand-operated switches located at the crossover between the RTT to the TTT were replaced with powered switches. Four powered switches and two additional manual switches are monitored in nearby equipment bungalows by object controllers. In the case of the powered switches, the object controllers have the functionality to not only monitor the position of the switches, but to also control the switch position when the system is set up in V–PTC mode. In this mode of operation, the object controllers monitor switch positions, as well as the aspect of the switch indicator lights and the state of occupancy of the track (from the fouling boundary at one end to the boundary at the other end).

A pre-existing 8 × 10-foot Sermi aluminum bungalow was used to house the controls and electronics necessary for the powered switch and switch position indicator lighting at the north end (Post 100) of the RTT siding. At the south end of the siding, a new 10 × 10-foot Sermi aluminum bungalow (henceforth referred to as the 602 Bungalow) was installed. Figure 15 is a picture of the 602 Bungalow. New equipment installed in the bungalow included batteries and battery charger, vital relays, on station circuit electronics, lightning arrestors, Ansaldo STS Microlok II object controllers (used as WIUs), and a MeteorComm MCC 6100 radio.

Figure 15. 602 Bungalow at RTT Siding Turnout

5.5 PTC Test Bed Upgrades Documentation

A documentation package was created for the PTC Test Bed upgrades to add to TTC's facility documentation records. The documentation package included AutoCAD drawings for equipment installation and wiring interconnect diagrams as well as equipment description packages. The equipment installation drawings depicted the physical dimensions, location, and individual component layout within each of the three equipment bungalows affected by the upgrade: (1) the 602 Bungalow, (2) the Post 100 Bungalow, and (3) the Instrumentation Case # 1 Bungalow, which is a small bungalow used for housing track signals equipment. Text-based wiring lists developed during the point-to-point interconnection of individual track signal components were used to generate physical wiring interconnect drawings for each component. Equipment description packages included vendor-provided documentation for each individual upgrade component.

6. V–PTC System Testing and Results

During development of the V–PTC system, tests were conducted at TTC using the resources of the PTC Test Bed. Testing occurred at the end of major build cycles, and the test results were reported to the V–PTC technical advisory group. Detailed test reports for each build were produced by LMC.[1,2,3,4,5] With permission from LMC, portions of each of the following sections on test results are either summarized or directly extracted from LMC reports.

6.1 Build 1 Testing—Train Location Monitoring

Testing for Build 1 occurred in March, April, and June of 2008. Since the capabilities developed in Build 1 were associated with train location monitoring, the goals of Build 1 testing were (1) to perform on-track testing of the LDS as it relates to position accuracy, speed accuracy, and route determination per the V–PTC SRS Build 1 performance requirements, and (2) to exercise Build 1 functional requirements and tests related to train location reporting and data logging. To accomplish these goals, LMC published a test plan,[9] which included the following types of testing:

- Locomotive position and speed tests on the RTT
- Direction and movement tests on the RTT
- Route determination tests (through switches and the Balloon Loop)
- Slide tests (wheel traction loss while braking) on a section of the RTT
- Slip tests (wheel traction loss during acceleration) on a section of the RTT
- GPS multipath tests on the RTT

6.1.1 Position and Speed Testing

Tests for determining position and speed accuracy were conducted at speeds of 10, 40, and 75 mph and at variable speeds (5–90 mph). Lap directions around the RTT were in clockwise (CW) and counterclockwise (CCW) directions, and testing included test configurations with high GPS visibility and with inhibited system GPS inputs (see Figure 16). There were a total of 16 test cases during this portion of testing.

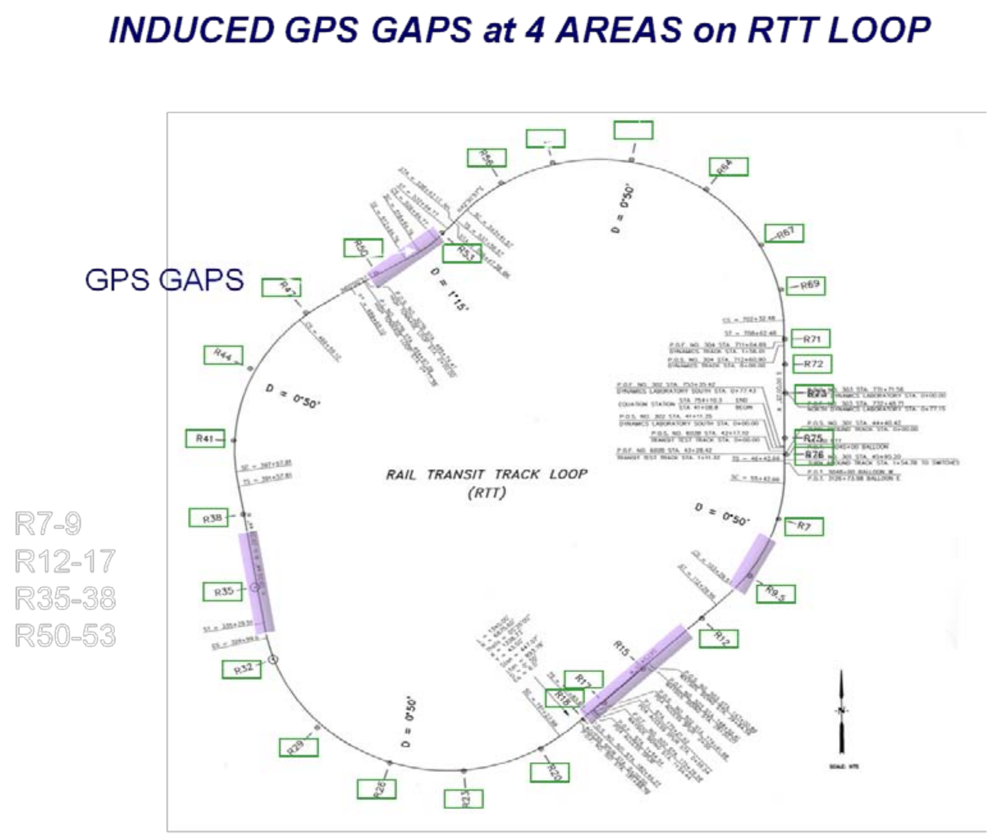

Figure 16. Areas of Induced GPS Gaps on RTT

6.1.2 Direction and Movement Testing

Tests for verifying accurate location reports were conducted on a limited section of RTT at 10 mph. During the tests, the locomotive (1) moved forward 1,000 ft from its initial position, (2) stopped, (3) went back 500 ft, (4) stopped, (5) moved forward another 1,000 ft, and finally, (6) went back 500 ft again. Then, this cycle of six steps was repeated a number of times. During these test cycles, the locomotive engineer performed a combination of normal stops and lurch (abrupt) stops. These cycles included some cycles with high GPS visibility and some with inhibited system GPS inputs. There were 34 test cases.

6.1.3 Route Determination Testing

Route determination testing was conducted to verify the LDS was accurately determining routes taken through switches. For this testing, some test runs were accomplished with the locomotive moving through RTT switches at 1, 5, 10, and 20 mph, and some runs were conducted on the Balloon Loop. For the runs through the switches, movements were in both CW and CCW directions of travel. These runs evaluated the system's ability to correctly track movements of both normal and diverging routes through the switches. Some runs were with high GPS visibility and some were with inhibited GPS performance. During the test runs, the V–PTC BOS was monitored in real time to verify that proper location reports were being received. There were 192 test cases.

For the test runs around the Balloon Loop, the locomotive traveled around the loop at 20 mph. For the two test cases, one traveled CW and the other traveled CCW.

6.1.4 Slide Testing

Slide testing was conducted to assess LDS location determination performance in the event of wheel slide while braking. Tests occurred along a 1,000-foot portion of the RTT. Liquid detergent was applied to the top of the rails on ~100-foot section of track directly preceding the planned stopping point (see Figure 17). The locomotive traveled over the test section at 10 mph, and then attempted to stop at or slightly after the end of the 100-foot soaped section. Four test cases were performed with both high and inhibited GPS visibility.

Figure 17. Soap Applied on Top of Rails

6.1.5 Slip Testing

Slip testing was intended to assess LDS location determination performance in the event of wheel slip during acceleration. As with slide testing, test runs occurred on a 1,000-foot portion of RTT where liquid soap had been applied to the top of the rails for the first 100 ft of the test section. However, in this case, liquid soap was also applied to the locomotive's wheels just before the start of each run. Then, the locomotive accelerated to 10 mph amid wheel slip, traversed the test section, and attempted to stop at or slightly after the end of the 1,000-foot soaped section. Testing included one test with high GPS visibility and one test with inhibited system GPS inputs.

6.2 Build 1 Test Results

Detailed Build 1 test results are in LMC's Build 1 Test Report.[1] An overview summary of the results, some of which are extractions from the report, are presented (with permission) in this section.

6.2.1 Position and Speed Testing

The intent of the position and speed testing was to determine how accurately the LCU places the locomotive along the track under various speeds, accelerations and decelerations, and GPS visibility conditions. In addition, speed accuracy is assessed using the same data sets.

Two V–PTC system performance requirements from SRS Section 8.1 are addressed:

- The V–PTC system shall determine the position of the leading end of the V–PTC controlling locomotive along the track with an accuracy of ≤ 15 ft, at a confidence level of 99 percent.
- The V–PTC system shall determine the speed of the train along the track with an accuracy of ≤0.5 mph, at a confidence level of 99 percent.

Locomotive Position Location Offset Results - Full GPS Coverage

A total of 16 RTT loop tests were conducted (216 miles), eight traveling CW and eight traveling CCW. In on-track tests, half of the 16 RTT Loop tests were conducted with continuous GPS outages ranging from 1,000 to 8,000 ft in distance. Figure 18 shows a summary of the results.

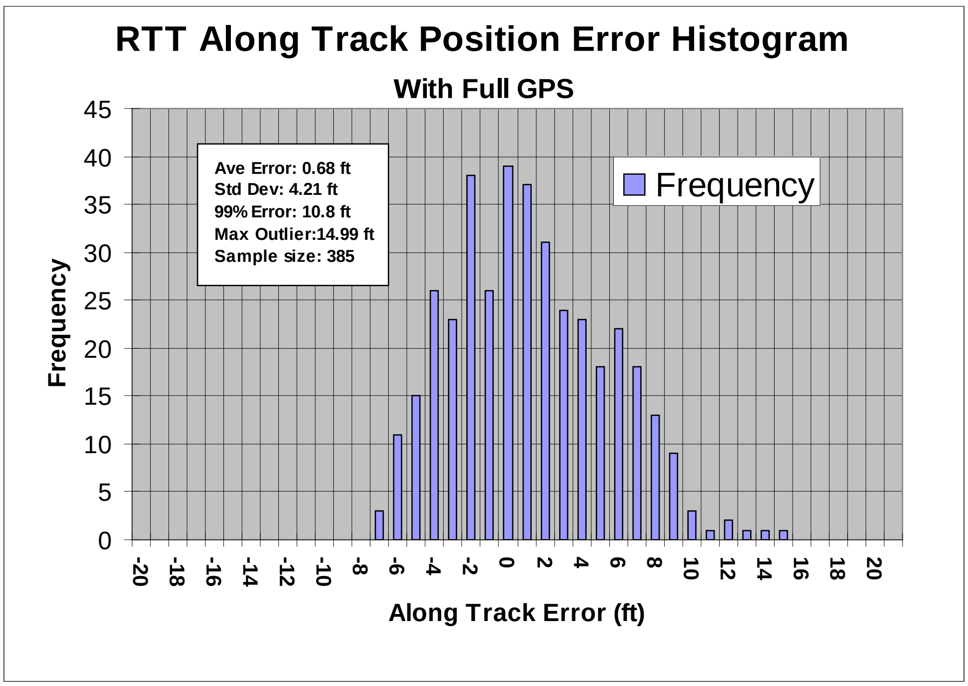

Figure 18. Position Location Errors - Full GPS

The average offset error is 0.68 ft and the standard deviation is 4.21 ft. The 99 percent value is 10.8 ft, using over 385 data samples. The requirement is 15 ft at 99 percent. The maximum outlier is 14.99 ft. An inspection of the location reports indicated that they were generated correctly.

Locomotive Position Location Offset Results - Inhibited GPS Coverage

Figure 19 shows the results of the same analysis, being performed with GPS RF signal switched out of the LCU input between the flags listed above. The average offset error is -0.14 ft, using over 403 samples, and the 99 percent value is 12.1 ft. The maximum outlier value is 17.1 ft. Location reports were generated correctly.

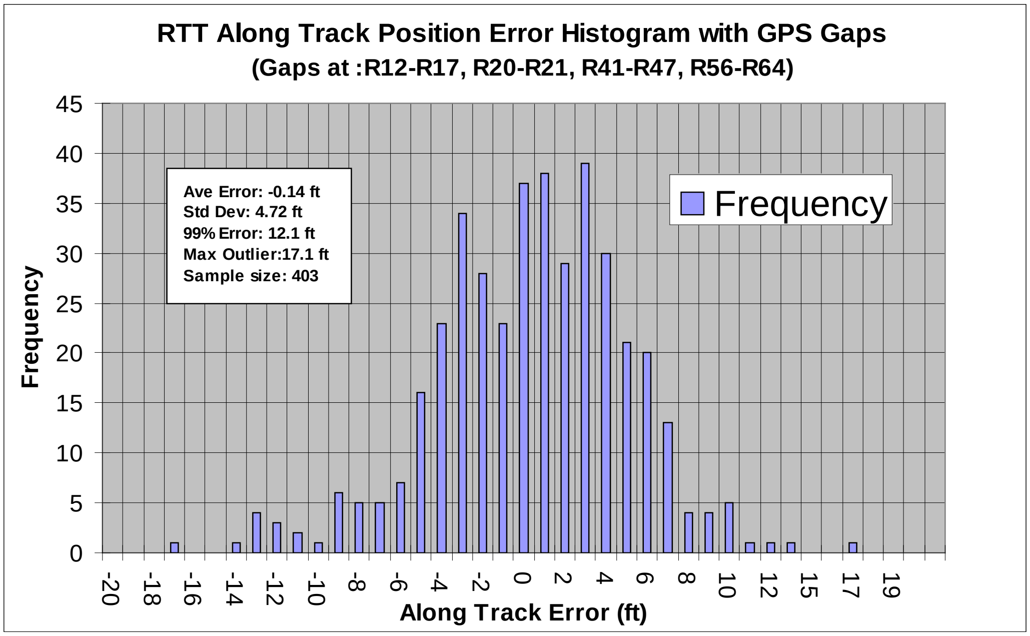

Figure 19. Location Errors – Inhibited GPS

Speed Accuracy Results—Full GPS Coverage

Figure 20 illustrates speed accuracy for the eight RTT runs with GPS enabled. The average error is -0.03 mph, and the computed 99 percent value is 0.54 mph. The requirement is 0.5 mph (99 percent). The maximum speed error computed is 0.485 mph, indicating that the computed 99 percent value is too conservative in this case, due to the slightly right skewed distribution of errors.

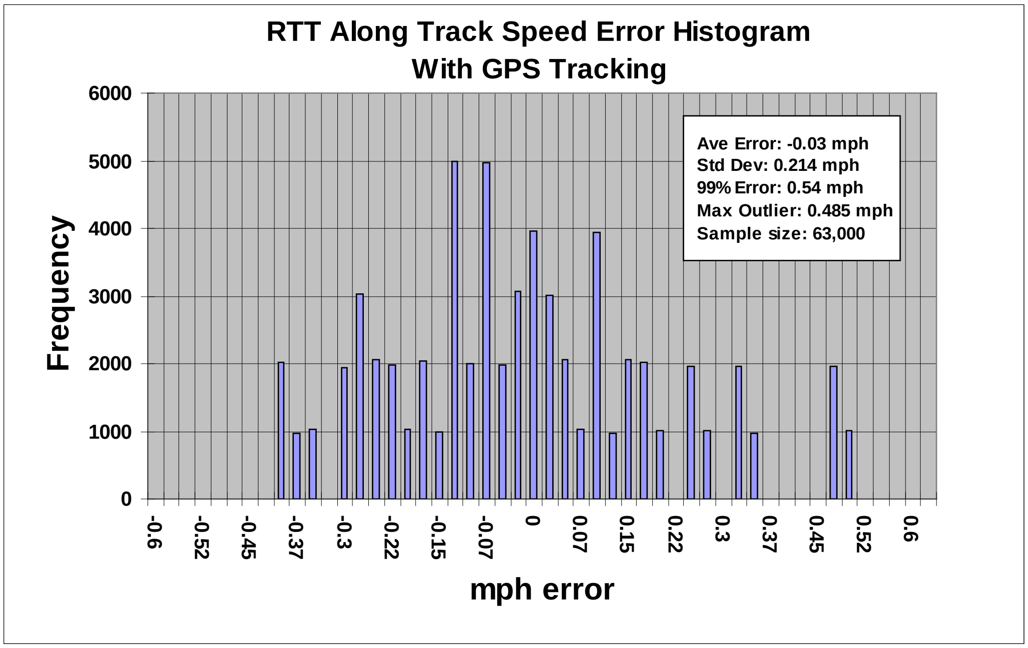

Figure 20. Locomotive Speed Errors – Full GPS

Speed Accuracy Results—Inhibited GPS Coverage

Figure 21 shows the results of locomotive speed errors with inhibited GPS coverage. GPS tracking was disabled continuously and at all times through the speed trap (R12-R17), just over 5,000 ft in length. The average error in speed is 0.001 mph, and the 99 percent value is 0.500 mph. This is slightly better than with continuous GPS tracking. The maximum speed error noted is 0.487 mph, slightly greater than with GPS tracking enabled (0.485 mph). The differences are statistically insignificant.

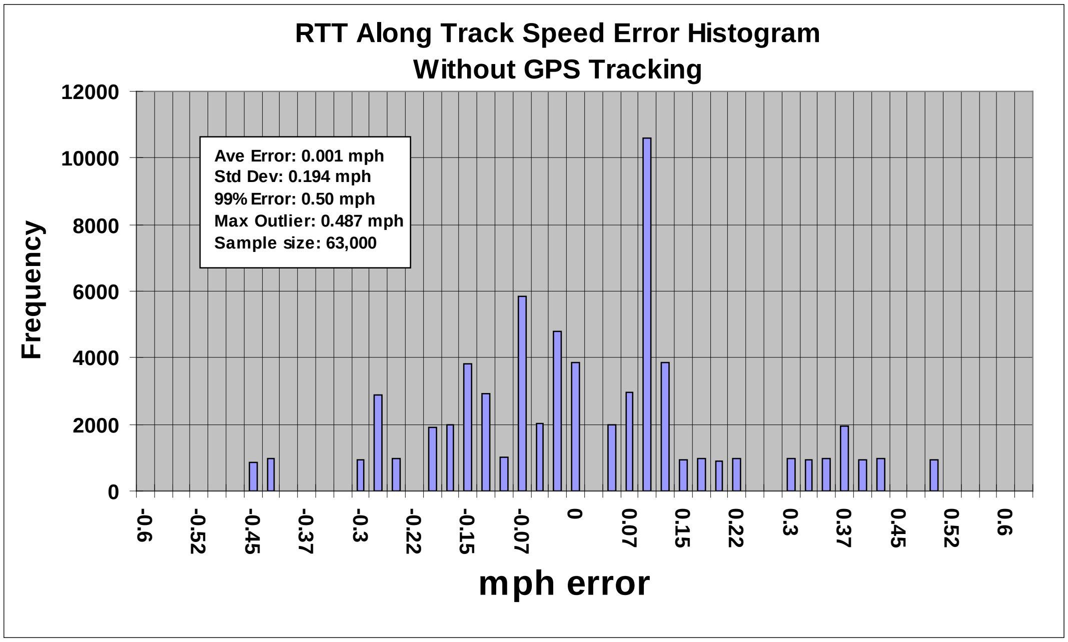

Figure 21. Loco Speed Errors – Inhibited GPS

6.2.2 Direction and Movement Testing

The intent of the direction and movement tests was to evaluate the ability of the LCU to keep track of direction and movement under a long series of direction changes. Direction and movement testing was conducted between R12 and R17 on a tangent section of the RTT. This testing consisted of moving the locomotive at 10 mph between R12 and R17 in a 1,000-foot forward, 500-foot back, 1,000-foot forward repetitive motion until the R17 marker was reached. There were 17 separate movements with normal stops and 17 movements with lurch (abrupt) stops. Two data sets were generated that spanned R12-R17 travel, one for normal stops and the other for lurch stops. The normal stop maneuvers spanned about 1,750 seconds, and the lurch stop maneuvers spanned about 1,840 seconds. All stop and start movements were detected correctly, as reported in the train location reports.

Direction and Movement with GPS

Figure 22 illustrates the along track offset error for the 34 individual movements (lurch and normal stops) combined. The average error is -0.9 ft. There are 84 data points evaluated. The maximum error noted was -5.58 ft. The standard deviation is 2.35 ft. The 99 percent value is 6.04 ft.

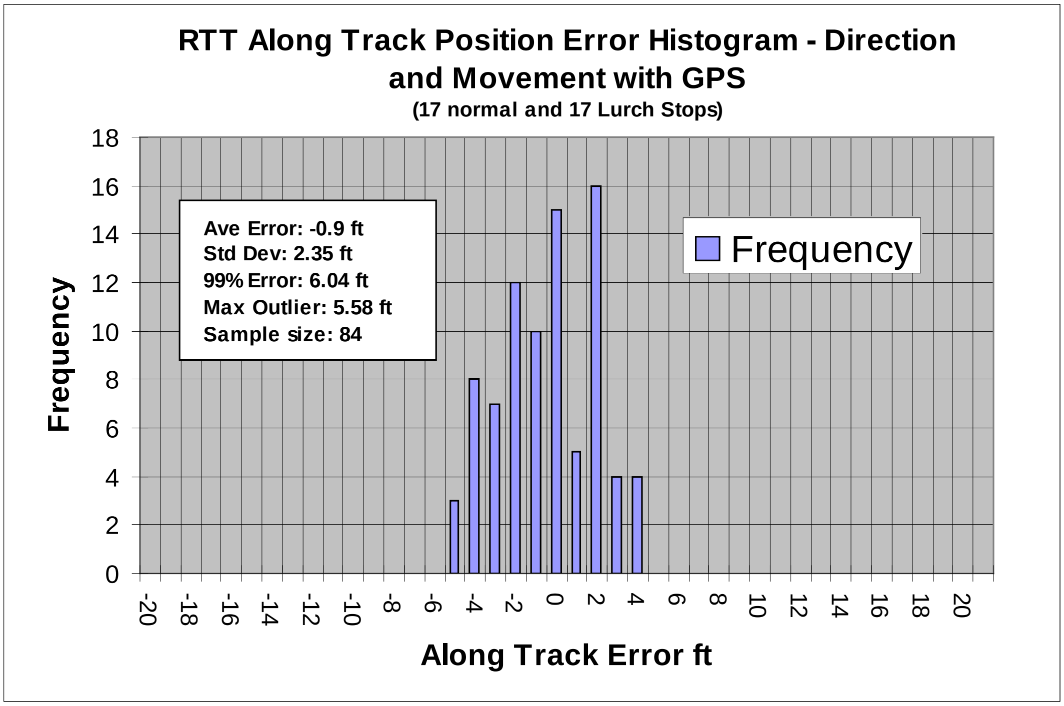

Figure 22. Direction and Movement Errors with GPS

Direction and Movement without GPS

On the basis of the 166 data samples, the average offset error is 1.87 ft, and the standard deviation is 6.19 ft. The standard deviation was at first too high to generate meaningful 99 percent statistics from this dataset. Bootstrapping was again used to resample the data 380 times. The recomputed standard deviation is also 6.19, and the 99 percent value is 15.9 ft. The maximum offset error is 19.42 ft. This sample and the one at 16.9 ft were the only two points that exceeded the specification out of the original 166 data samples. Within the data span of ~1,800 seconds, the percentage of time without GPS tracking is ~85 percent. Train location reports were generated correctly in all movements.

6.2.3 Route Determination Testing

The intent of this test was to measure the ability of the LCU to autonomously determine which path is taken through the switch, without having knowledge of the switch position from external sources. This LCU was field tested in full GPS and complete GPS outage configurations. Six switches were included in the route determination tests. They are Switch 304, Switch 303, Switch 301, Switch 801, Switch 602B, and Switch 501. Each route determination test consisted of running through the switch at speeds of 1.5, 5, 10 mph and (except for Switch 303) 20 mph, in both directions, in both normal and diverging configurations, for a total of 32 path tests for each switch. For No. 20 switches like Switch 602B, the time it took to travel from the facing point fouling limit to the normal or diverging clearance points was in the 180-second range. Each test was conducted with full GPS visibility and with GPS signals inhibited (RF switch controlled). For GPS gap tests, anytime the locomotive was between the facing point fouling limit and normal or diverging clearance point, GPS was inhibited via RF switch. A total of 188 separate path tests were conducted.

In addition to switch path determination testing, a special Balloon Loop test was also performed. The Balloon Loop was traversed in both the CW and CCW directions at 20 mph and track selection was monitored. Switch 303 cannot be taken at 20 mph, so testing was performed at 1.5, 5, and 10 mph. The test laptop, mounted in the cab and running LDS monitor software, was watched to ensure that the partition identification changed appropriately when the locomotive took a switch in a diverging direction.

Switch Tests with GPS Tracking Enabled

Results (using the software deployed during the actual testing on the locomotive) indicate that **all** switch paths were correctly identified with GPS enabled.

Switch Tests with GPS Tracking Inhibited

With GPS disabled between the clearance points and fouling limits, a first attempt error was noted at Switch 801 diverging at 1.5 mph traveling forward. The second on-track attempt was successful. This also occurred at the Switch 602 at 1.5 mph during the diverging move traveling forward. The second on-track attempt was also successful. Out of 188 tests, two were failures, for an initial 98.93 percent success rate.

Balloon Loop Test with GPS Tracking Enabled

For this test, locomotive travel started just north of Switch 301 position with short hood forward, traveling CW around the loop until the start point was reached with the rear of the locomotive. Then the trip was taken long hood forward, retracing the path CCW. All movements were at 20 mph. The degree of curvature at the bottom of the loop is 7.6 degrees per 100 ft. Total loop length is 8,200 ft.

Balloon Loop Test with GPS Tracking Inhibited on Loop

In this analysis, GPS tracking was inhibited at all times when actually traveling around the loop. Note that in the short hood forward direction the error builds up without GPS quite rapidly, until GPS is enabled at the Switch 301 to Switch 801 area, peaking at -131 ft. On the return (long hood forward) trip, the error buildup was ~0.166 what it was in the short hood forward direction. The loop is ~8,200 ft in length along the track centerline. The rate of along track error growth without GPS in the short hood forward direction is 0.0159 ft error per ft traveled. In the long hood forward direction, the error accumulated at a rate of 0.00268 ft per ft traveled.

6.2.4 Slide Testing on the RTT

The intent of slide testing was to evaluate the location performance of the LCU in the presence of sustained wheel slide, because wheel tachometer data is one of the sensor inputs the LCU uses for location determination on the rail network. Slide testing was conducted between R12 and R13. Water was sprayed on the track just in front of the locomotive as it passed by. The locomotive’s automatic sander was disabled. In slide testing, the intent was to measure the LCU computed offset at the surveyed flags at R12, R12+500, and R13, and compare these values with known separations. Figure 23 is a graphic that depicts the results. The data from these tests indicates the offset errors measured between R12 and R13 are well within the 15 ft requirement.

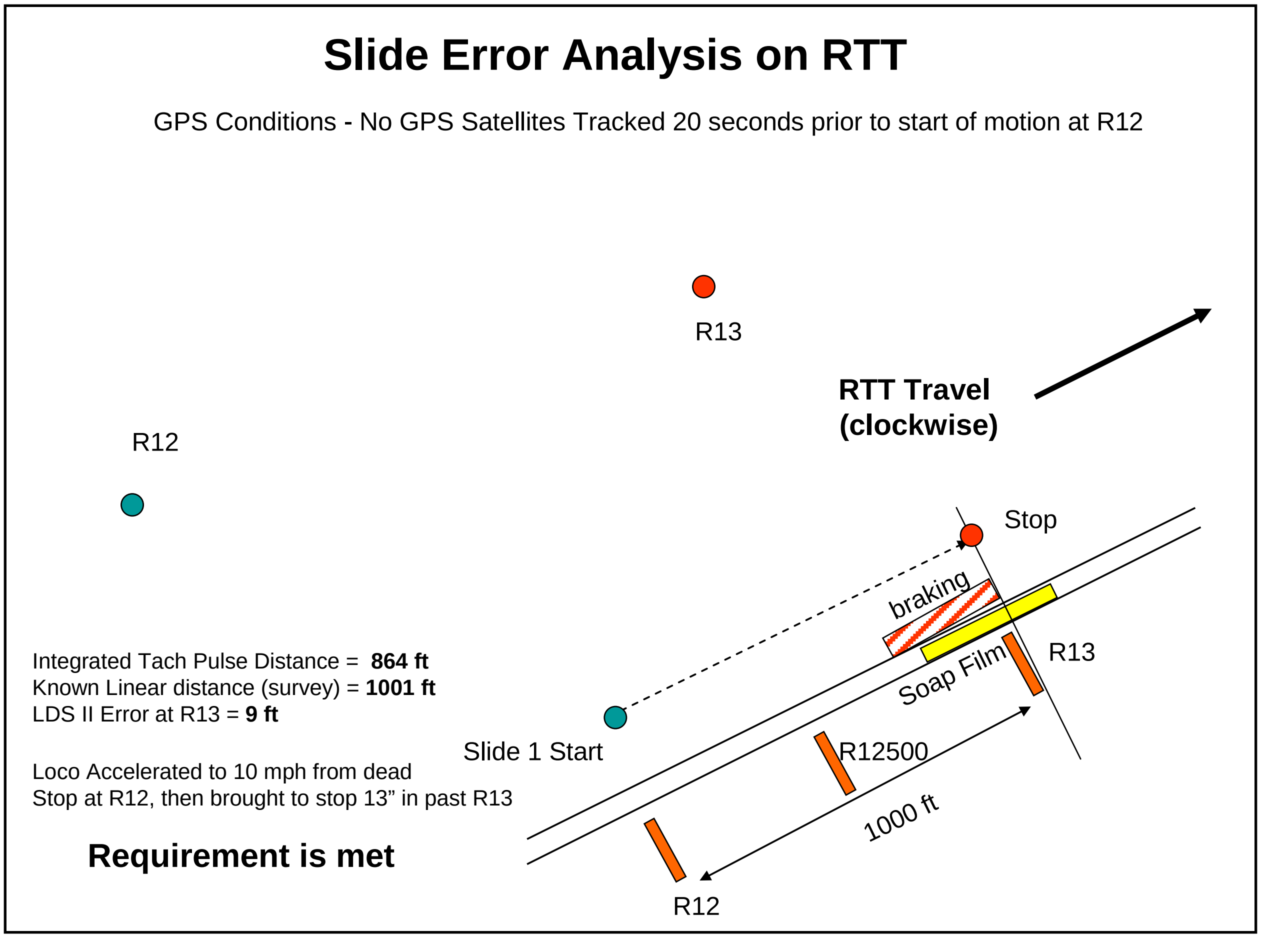

Figure 23. Slide Testing Results

6.2.5 Slip Testing on the RTT

The purpose of slip testing was to evaluate the location performance of the LCU in the presence of sustained wheel slip. The data analyzed from the June 2008 testing does not indicate that wheel slip was ever developed. Data taken from slip attempts indicate good slip was generated. The two flags are 1,000 ft apart, but the tachometer input based distance is 1,119 ft, resulting in a 119-foot error if tachometer was used without the benefit of GPS tracking. The small and large slips can clearly be seen in Figure 24, reaching a peak rate of ~35 ft/s (23 mph) while traversing across the slippery section of track during acceleration from a stop. The nominal speed peak (without slip) is reached midway through the data set, ~23 mph, consistent with the actual speed from the test plan.

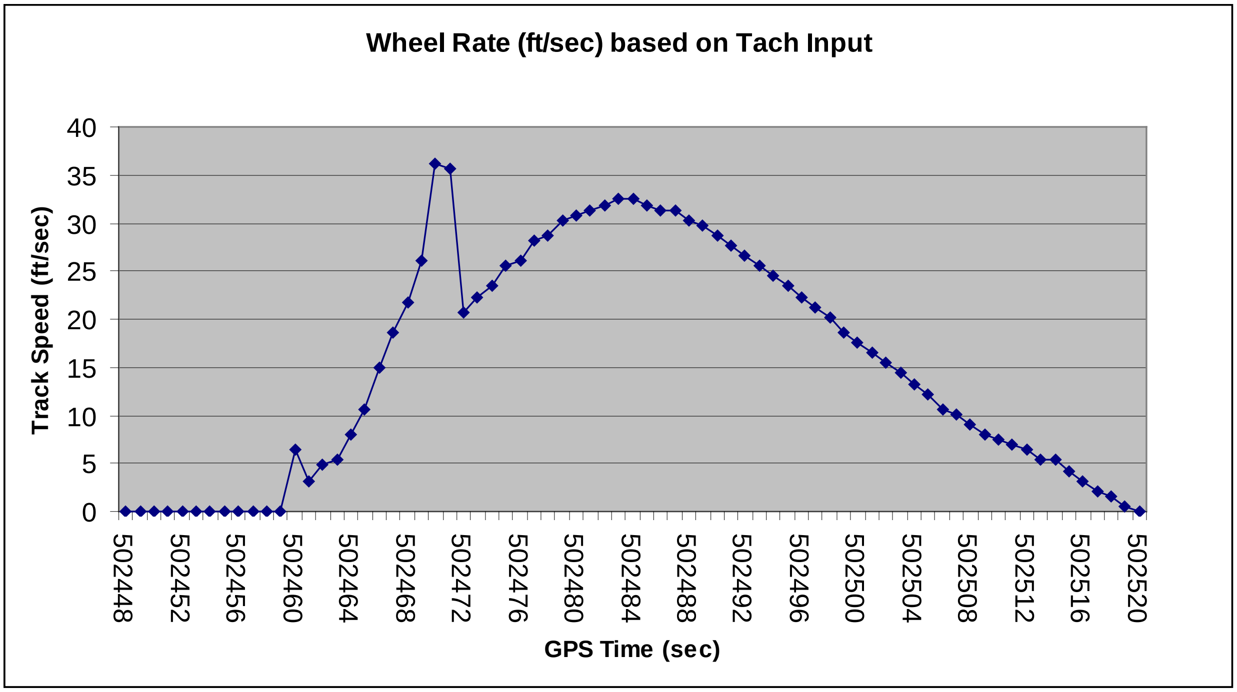

Figure 24. Wheel Rate during Slip Testing

6.3 Build 2 Testing – Server Switch Monitoring

The goal of Build 2 testing was to evaluate how well the V–PTC BOS Switch Monitoring functionality complied with the requirements identified in V–PTC SRS, Revision 1. June 2008 testing included the following specific test events:

- Test 2 Events
  - Display software version at the system management console
  - Correct date/time synchronization with coordinated universal time (UTC)
  - Password control of the system management console
- Test 4 Events
  - Verify wayside software revision level is compatible
  - Retry communications after initialization failure (negative communications)
  - Retry communications after communications outage (lost and regained communications)
  - Software revision level incompatibility aborts wayside device
- Test 5 Events
  - Subdivision and operational synchronization and status of wayside devices
  - Time synchronization of V–PTC BOS and wayside devices
- Test 6 Events
  - Monitoring the power-operated switch states and occupancy
  - Monitoring of hand-operated switch status
  - Configurable reporting rate of wayside devices
- Test 7 Event
  - Logging message communications

To support conducting the Build 2 test events, TTCI implemented two switch simulations, one hand-operated and one power operated, in an onsite laboratory at TTC. Two object controllers were programmed and configured as planned for testing. One object controller was configured as a hand-operated switch and represented Switch 301 on the TTC test track. The Switch 301 object controller was connected to a switch emulation box that provided switch open and closed status. The other object controller was configured as a power-operated switch with an overswitch track circuit.

This configuration represented Switch 602B. This object controller was directly connected to a fully functional power-operated switch and switch emulation box that provided overswitch occupancy status. Both object controllers were programmed to support initialization and switch status messaging to the V–PTC BOS. The hand-operated switch configuration provided both Normal and Unknown switch states, while the powered switch configuration provided Normal, Unknown, Reverse, Track Circuit Unoccupied, Track Circuit Occupied, Local, and Remote Control switch states and status.

6.4 Build 2 Test Results

Detailed descriptions of the Build 2 test results are contained in LMC's Build 2 Test Report.[2] A summary of the report's content appears below.

All but one test passed during three days of testing. A Problem Report (PR-15) was written to address this problem. Table 1 summarizes the results of all testing performed.

Table 1. Build 2 Tests and Results

Test ID	Test Number	System Specification Paragraph	Procedure Name	Pass/ Fail
1	Test 2	5.5.1	V–PTC Displays Software Version at the System Management Console	P
2	Test 2	5.12	V–PTC Date/Time Synchronization with UTC	P
3	Test 2	10.1	V–PTC Password Control of the System Management Console	P
4	Test 4	5.1.3.1	Verify Wayside Software Revision Level is Compatible	P
5	Test 4	5.1.3.1	Retry Communications for Software Revision After Initialization Failure (Negative Communications)	P
12	Test 4	5.1.3.1	Retry Communications for Software Revision After Communications Outage (Lost and Regained Communications)	P
13	Test 4	5.1.3.1	Software Revision Level Incompatibility Aborts Wayside Device (Also verified—Wayside Software Includes Version Identifier; Wayside Software Version Displays at System Management Console; Normal Operations for Successful Wayside Software Revision Check	F
6	Test 5	5.1.1.3	Subdivision and Operational Synchronization and Status of Wayside Devices	P
7	Test 5	8.2.C	Time Synchronization of V–PTC Server and Wayside Devices	P
8	Test 6	4.5.1	Monitoring the Power-Operated Switch States and Occupancy	P
9	Test 6	4.5.1	Monitoring of Hand-Operated Switch Status	P
10	Test 6	4.5.1	Configurable Reporting Rate of Wayside Devices	P
11	Test 7	5.6	Logging Communications	P

In summary, 12 of 13 tests completely passed during the formal test period. The failure in Test ID 5 took place on one section of the test resulting in the V–PTC BOS not initializing the wayside device, but at the same time not failing the device as required. All other tests passed without any errors.

6.5 Build 3 Testing – Switch Warnings and Control

Build 3 testing occurred in October of 2008. The goals of Build 3 testing were to:

- Perform on-track testing of the V–PTC system's onboard Train Borne capabilities per the V–PTC SRS Build 3 SRS.
- Exercise Build 3 functional requirements and tests related to onboard display of track location, switch state, train speed, and date and time; and related to functionality of locomotive power-up checks and health monitoring, as well as communications logging.

As a brief summary, Build 3 Test Plan events included the following:

- Onboard display of train location
  - Display of *track configuration* within horizon
  - Display of *switch state*
  - Display of *train speed*
  - Display of *date and time*
  - Configurability of display *horizon size*
- Locomotive power-up checks
  - *Integrity* check
  - *Software version* check
- Locomotive health monitoring
- Communications logging

Build 3 testing was conducted on the RTT for all tests that required movement or verification of track features displayed on the LDU display. Turnouts onto and return entry to the RTT from the Train Dynamics Track, TTT, and the Balloon Loop were also executed. Tests that did not require movement were conducted in the yard tracks near the Center Services Building. New components for the Build 3 tests included the MCC-6100 radios and the LDU. Figure 25 shows the PTC Test Bed communications configuration using components added for Build 3 testing.

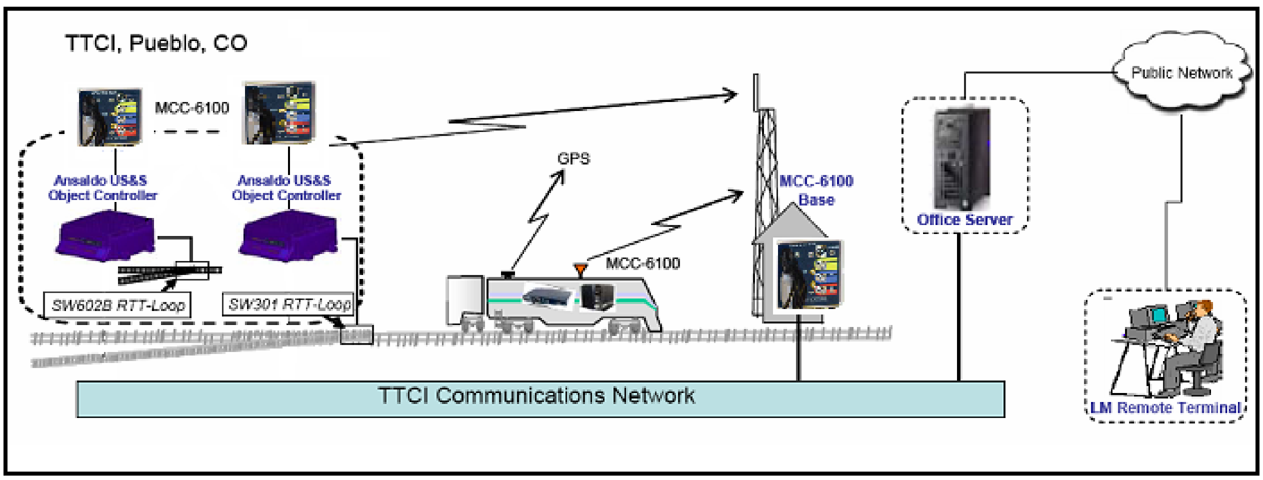

Figure 25. TTCI Communications Network

Testing activities were conducted primarily in the cab of Locomotive 2001, either on the RTT or in the yard. Figure 26 shows personnel conducting tests in Locomotive 2001.

Figure 26. Build 3 Testing on Locomotive 2001

Figure 27 is a graphic depicting the information displayed by the LDU.

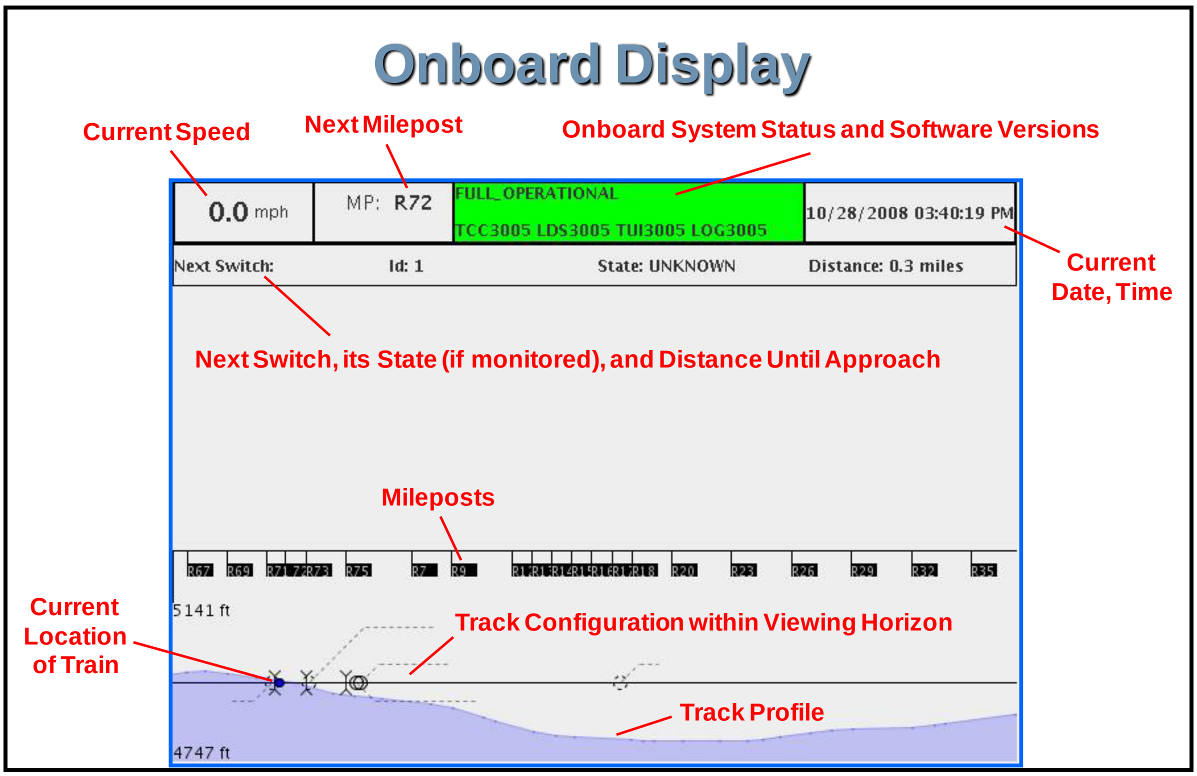

Figure 27. Graphic of LDU Display on Locomotive 2001

During testing, a laptop was connected to the onboard LAN to allow for test configuration, test support, and test monitoring activities. Additionally, some support activities were accomplished from the TTC Operations Building, including saving logs upon completion of a test, creation of configuration files needed for the tests, system configuration, and system initialization.

6.6 Build 3 Test Results

Detailed descriptions of the Build 3 test results are contained in LMC's Build 3 Test Report.[2] Table 2 shows a summary of Build 3 test results. Table 3 shows the details of Build 3 test results.

Table 2. Overview Summary of Build 3 Test Results

System Test Step Summary	Total Steps	Percentage
Total Steps Executed – Passed	488	89.5
Total Steps Passed Conditionally	0	0.0
Total Steps Failed	7	1.3
Total Steps Blocked	50	9.2
Total Steps Not Executed	0	0.0

Table 3. Build 3 Tests and Results

System Test Procedure	Date Executed	NE	P	PC	F	BL	Total Steps	Test Status
LOCO-100: Track Config & Train Location	10/20/2008	0	94	0	3	14	111	Partial Pass
LOCO-110: On-board Switch Awareness	10/20/2008	0	34	0	1	0	35	Partial Pass
LOCO-120: Horizon Size Configuration	10/21/2008	0	101	0	0	0	101	Pass
LOCO-130: AG AI - 40 MPH thru Switch 301	10/21/2008	0	56	0	0	0	56	Pass
LOCO-200: On-board Power-up Integrity								
Test Case 1: Fault Free Environment	10/21/2008	0	27	0	0	0	27	Pass
Test Case 2-1 to 2-5: HW Fault Insertion	No Build 3 testing - No H/W failure reporting							Deferred
Test Case 3-1: S/W Fault Insertion	10/21/2008	0	17	0	0	4	21	Partial Pass
Test Case 3-2: S/W Fault Insertion	10/21/2008	0	22	0	0	4	26	Partial Pass
Test Case 3-3: S/W Fault Insertion	10/21/2008	0	20	0	0	4	24	Partial Pass
LOCO-210: On-board S/W Versions								
Test Case 1: Acceptable Versions	10/21/2008	0	18	0	0	0	18	Pass
Test Case 2: Interrupt Comms - Version	No Build 3 testing - Could not create environment to demonstrate							Deferred
Test Case 3: Incompatible Version	10/21/2008	0	29	0	1	6	36	Partial Pass
LOCO-300: On-board Health Monitoring								
Test Case 1: Fault Free Environment	10/22/2008	0	25	0	0	0	25	Pass
Test Case 2: Interface Fault Inserted	10/22/2008	0	16	0	0	5	21	Partial Pass
Test Case 3 and 4: S/W Fault Insertion	No Build 3 testing – No S/W or Dataset fault insertion with system executing							Deferred
Test Case 5: Loco Non-Comm Recovery	10/22/2008	0	20	0	0	2	22	Partial Pass
LOCO-400: Messaging Logging	10/22/2008	0	9	0	2	11	22	Partial Pass
System Test Step Totals		**0**	**488**	**0**	**7**	**50**	**545**	

Build 3 test results are summarized by test steps performed, test procedures performed, and requirements tested. The test step results categories used for the Build 3 tests are defined as follows:

- Passed—Step was executed and the expected results were successfully observed
- Passed Conditionally—Step was executed using a workaround or alternative to the stated action to successfully observe the expected results
- Failed—Step was executed and the expected results were not observed successfully

- Blocked—The step could not be performed due to either a system problem (PR), a functional capability not delivered with the build, test conditions that could not be achieved to demonstrate the requirement, or any other conditions that prevented execution of the stated actions
- Not Executed—Step was not executed

The pass/fail status of each Build 3 requirement was also analyzed by determining the results of each step when a specific requirement was referenced. The status of a requirement was then classified into one of the following categories:

- Passed—All steps referencing the requirement passed
- Partial Pass—There was a mixture of passed and either failed or blocked steps referencing the requirement
- Failed—All steps referencing the requirement failed
- Blocked—All steps referencing the requirement were blocked

Table 4 is a summary of the requirement totals for each of the above categories.

Table 4. Summary of Requirements Results

	Total Requirements
Pass	13
Partial Pass	12
Fail	0
Blocked	11

6.7 Build 4 Testing–Onboard Display of Authority

Build 4 testing occurred in two phases, referred to as Build 4A and Build 4B. Build 4A testing occurred in December 2008 and January 2009, and Build 4B testing occurred in April and May 2009.

6.7.1 Build 4A Testing

The goals of Build 4A testing were to:

- Perform on-track testing of the V–PTC system's ability to command a powered switch remotely per the V–PTC SRS, Build 4A performance requirements
- Exercise Build 4A functional requirements and tests related to commanding the switch remotely and verifying switch states at the locomotive, the office server, and the object controller
- Test commands from the server with the switch in different states: normal, reverse, unknown, LCM, and overswitch protection.

An outline summary of the Build 4A Test Plan includes testing of:

- Remote control of switch from office server to demonstrate
  - Successful control of power-operated switch

  - Object controller's response to commands from server while in over-switch protection
  - V–PTC server's rejection of switch commands
  - Object controller's response to commands from server while in local control mode
- Communication outages during switch commands
- Communications logging

6.7.2 Build 4A Test Results

Table 5 is an overview summary of the Build 4A test results.

Table 5. Summary of Executed Test Steps

System Test Step Summary	Total Steps	Percentage of Total Steps
Total Steps Executed – Passed	1205	98.85
Total Steps Passed Conditionally	0	0.0
Total Steps Failed	3	0.25
Total Steps Blocked	0	0.0
Total Steps Not Executed	11	0.9

Build 4A test results are summarized by test steps performed, test procedures performed, and requirements tested. These detailed results of Build 4A testing are recorded in Table 6. The test step results categories used across the Build 4A tests are defined as follows:

- Passed—Step was executed and the expected results were successfully observed
- Passed Conditionally—Step was executed using a workaround or alternative to the stated action to successfully observe the expected results
- Failed—Step was executed and the expected results were not observed successfully
- Blocked—The step could not be performed due to either a system problem a functional capability not delivered with the build, conditions that could not be achieved to demonstrate the requirement, or any other conditions that prevented execution of the stated actions
- Not Executed—Step was not executed

Note that there are five defined categories of testing:

- Successful control of powered switches
- Overswitch Protection causes Switch Change Command Failures
- V–PTC Server Rejects Switch Change Commands
- LCM causes Switch Change Command Failure
- Communications Outages during Switch Change Commands

Table 6. Detailed Build 4A Test Results

System Test Procedure	Date Executed	P	PC	NE	BL	F	Total Steps	Test Status
SWCNTL-100: Successful Control of Powered Switches								
Test Case 1	12/18/2008	52	0	0	0	0	52	Pass
Test Case 2	12/18/2008	49	0	0	0	0	49	Pass
Test Case 3	12/18/2008	55	0	3	0	1	59	Partial Pass
Test Case 4	1/23/2009	82	0	0	0	2	84	Partial Pass
SWCNTL-110: Overswitch Protection causes Switch Change Command Failures								
Test Case 1	1/23/2009	63	0	0	0	0	63	Pass
Test Case 2	1/23/2009	64	0	0	0	0	64	Pass
Test Case 3	1/23/2009	67	0	0	0	0	67	Pass
Test Case 4	1/23/2009	59	0	4	0	0	63	Pass
SWCNTL-120: V–PTC Server Rejects Switch Change Commands								
Test Case 1	1/23/2009	54	0	0	0	0	54	Pass
Test Case 2	1/23/2009	42	0	0	0	0	42	Pass
Test Case 3	1/23/2009	54	0	0	0	0	54	Pass
Test Case 4	1/23/2009	54	0	0	0	0	54	Pass
Test Case 5	1/23/2009	42	0	0	0	0	42	Pass
Test Case 6	1/23/2009	54	0	0	0	0	54	Pass
SWCNTL-130: LCM causes Switch Change Command Failures								
Test Case 1	1/23/2009	67	0	0	0	0	67	Pass
Test Case 2	1/23/2009	64	0	0	0	0	64	Pass
Test Case 3	1/23/2009	67	0	0	0	0	67	Pass
Test Case 4	1/23/2009	66	0	0	0	0	66	Pass
SWCNTL-140: Communications Outages during Switch Change Commands								
Test Case 1	12/18/2008	47	0	0	0	0	47	Pass
Test Case 2	12/18/2008	56	0	4	0	0	60	Pass
Test Case 3	12/18/2008	47	0	0	0	0	47	Pass
System Test Step Totals		**1205**	**0**	**11**	**0**	**3**		

6.7.3 Build 4B Testing

The goals of Build 4B testing were to:

- Demonstrate switch control capability by the V–PTC system
- Validate the Build 4 switch control requirements identified in the V–PTC SRS, dated October 31, 2008.

The principal test objectives included evaluating the following V–PTC system functionalities:

- Remote control of powered switches from the RailComm CAD system.
- Monitoring of switch positions and state changes from the CAD system including:
    - Unknown and locked switch positions
    - Overswitch protection
    - LCM
- Train location monitoring on the CAD system
- System status updates displayed on the CAD system

The approach to Build 4B testing was to use an integrated CAD/BOS to demonstrate required functionalities. A commercially available CAD system from RailComm was interfaced and integrated with the V–PTC server by LMC and RailComm. All other system components remained the same as had been used for Build 4A test activities. Testing was based on using demonstration methods to validate all tested requirements and included the following test demonstrations:

- System Synchronization
    - V–PTC server/CAD system startup and synchronization
        - Starting V–PTC server before CAD
        - Starting CAD before V–PTC server
        - Communications outages and restarts of each
        - Verifying of CAD system software version number
        - Error conditions causing interface shutdown and restart
- Switch Monitoring and Control
    - Switch monitoring at CAD
        - Monitoring of hand-operated switches
        - Monitoring of power-operated switches
        - Communication outages and restarts of each
    - Switch control from CAD
        - Requesting switch changes from normal to reverse, reverse to normal, unknown to reverse and normal, and one position to the same position
        - Overswitch protection circuit
        - LCM
        - Testing timing and lockout conditions

System functionalities associated with location monitoring and system health were tested. Location monitoring included CAD system tracking, train initialization and CAD system displays, mile post verification on-screen and in messages, and direction of travel on the LDU.

System health included monitoring system health status information sent to CAD system, status of object controller communications health, and status of onboard Train Borne communications and system health.

6.7.4 Build 4B Test Results

Detailed descriptions of the Build 4B test results are contained in LMC's Build 4B Test Report.[4] The results are summarized in this section of the report.

During the formal test period, 46 out of 50 tests completely passed without errors. This is after taking away verification of logging events by the RailComm CAD system. The RailComm system has no logging requirements in the V–PTC SRS, and any failures in this area were not counted against the overall V–PTC system performance obtained during Build 4B testing. Table 7 provides the individual test case results and the statistical data used in developing the overall result percentages.

The following is a description of the fields included in Table 7.

- Date executed is the date the test was executed during the formal testing period.
- The column labeled P is the sum of nonrequirement and requirement laden test steps.
- The column labeled PC stands for passed conditionally. This means the results obtained for the test step did not change the overall results of the test case. For example, if the test was expecting a TS_DATA state change message as the next message but the wayside device had to be reset and after the reset the TS_DATA message was received with the expected state then this test step was mark passed conditionally.
- The column labeled NE stands for not executed. This labeled is used for all test steps not executed during the test. Reasons include cases in which two outcomes are possible depending on the timing of other actions in relationship to external stimulus.
- The column labeled BL stands for blocked. An earlier failure may block the execution of later steps. For example, an error causing a message to not be sent will cause a block of the acknowledgement message.
- The column labeled F stands for failed. This means the expected result did not happen.
- The Total Steps column is a sum of test steps in columns P, PC, NE, BL and F for each test case. This sum includes both the test case and the post analysis test steps.

The Test Status column is the overall passed/failed test results. A Partial Pass means some aspect of the test failed, but the V–PTC system performance was not compromised by the failure.

Table 7. Build 4B Test Case Results

System Test Procedure	Date Executed	P	PC	NE	BL	F	Total Steps	Test Status
SYSSYNC-50: Synchronization between the V-PTC Server and RailComm CAD								
Test Case 1	5/1/2009	31	0	0	0	0	31	Pass
Test Case 2	5/1/2009	28	0	0	0	0	28	Pass
Test Case 3	5/1/2009	25	0	0	0	1	26	Partial Pass
Test Case 4	5/1/2009	23	0	0	0	0	23	Pass
SWCNTL-100: Successful Control of Powered Switches								
Test Case 1	5/1/2009	63	0	0	0	0	63	Pass
Test Case 2	5/1/2009	58	0	0	0	0	58	Pass
Test Case 3	5/1/2009	76	0	0	0	0	76	Pass
Test Case 4	5/1/2009	145	0	16	2	4	167	Partial Pass
SWCNTL-105: Received Status of Hand-Operated Switch Positions								
Test Case 1	4/30/2009	59	0	0	0	0	59	Pass
Test Case 2	4/30/2009	39	0	0	0	0	39	Pass
SWCNTL-110: Over-Switch Protection causes Switch Change Command Failures								
Test Case 1	4/30/2009	84	0	0	0	0	84	Pass
Test Case 2	4/30/2009	83	2	0	0	0	85	Pass
Test Case 3	5/1/2009	88	0	0	0	0	88	Pass
Test Case 4	4/30/2009	76	0	0	0	0	76	Pass
Test Case 5	4/30/2009	81	0	0	0	0	81	Pass
Test Case 6	5/1/2009	90	0	0	0	0	90	Pass
SWCNTL-120: V-PTC Server rejects Switch Change Commands								
Test Case 1	4/30/2009	65	0	0	0	0	65	Pass
Test Case 2	4/30/2009	47	0	0	0	0	47	Pass
Test Case 3	5/1/2009	65	0	0	0	0	65	Pass
Test Case 4	4/30/2009	65	0	0	0	0	65	Pass
Test Case 5	4/30/2009	47	0	0	0	0	47	Pass
Test Case 6	5/1/2009	65	0	0	0	0	65	Pass
Test Case 7	5/1/2009	74	0	0	0	0	74	Pass
Test Case 8	5/1/2009	56	0	0	0	0	56	Pass
Test Case 9	5/1/2009	74	0	0	0	0	74	Pass
Test Case 10	5/1/2009	74	0	0	0	0	74	Pass
Test Case 11	5/1/2009	56	0	0	0	0	56	Pass
Test Case 12	5/1/2009	74	0	0	0	0	74	Pass
SWCNTL-130: Local Control Mode causes Switch Change Command Failures								
Test Case 1	4/30/2009	71	0	0	0	0	71	Pass
Test Case 2	4/30/2009	61	0	0	0	0	61	Pass
Test Case 3	5/1/2009	87	0	0	0	0	87	Pass
Test Case 4	4/30/2009	84	0	0	0	0	84	Pass
Test Case 5	4/30/2009	82	0	0	0	0	82	Pass
Test Case 6	5/1/2009	83	0	0	0	0	83	Pass
Test Case 7	4/30/2009	70	0	0	0	0	70	Pass
Test Case 8	4/30/2009	80	0	0	0	0	80	Pass
SWCNTL-135: Communications Outages while Monitoring Switches								
Test Case 1	4/30/2009	122	0	0	0	0	122	Pass
Test Case 2	4/30/2009	122	0	0	0	0	122	Pass
Test Case 3	4/30/2009	64	0	0	0	0	64	Pass

System Test Procedure	Date Executed	P	PC	NE	BL	F	Total Steps	Test Status
SWCNTL-140: Communications Outages during Switch Change Commands								
Test Case 1	4/30/2009	77	0	0	0	0	77	Pass
Test Case 2	4/30/2009	73	1	0	0	0	74	Pass
Test Case 3	5/1/2009	71	0	0	0	0	71	Pass
Test Case 4	5/1/2009	67	0	0	0	0	67	Pass
LOCMON-150: Location Monitoring and Train Status								
Test Case 1	4/30/2009	64	0	0	0	0	64	Pass
Test Case 2	4/30/2009	41	0	0	0	0	41	Pass
Test Case 3	5/1/2009	33	0	0	0	0	33	Pass
Test Case 4	5/1/2009	48	0	0	0	0	48	Pass
HEALTH-160: Error Detection and Health Monitoring								
Test Case 1	5/1/2009	28	0	0	3	1	32	Fail
Test Case 2	5/1/2009	19	0	0	1	1	21	Fail
Test Case 3	5/1/2009	114	0	0	0	0	114	Pass
System Test Step Totals		**3372**	**3**	**16**	**6**	**7**		

Test ID	System Test Procedure	Date Executed	NE	P	PC	F	BL	Total Steps	Test Status
TRNTERM-110 -- CAD Initiated Train Termination Requests									
178	Test Case 1	12/18/2009	0	19	0	0	0	19	Passed
179	Test Case 2	12/18/2009	16	5	0	0	0	21	Partial Test
TC-001 -- Onboard Power-On Tests									
182	Test Case 1 (TC-001-1A)	12/1/2009	0	6	0	0	0	6	Passed
184	Test Case 3 (TC-001-2)	12/1/2009	0	7	0	0	0	7	Passed
185	Test Case 4 (TC-001-3A)	12/1/2009	0	8	0	0	0	8	Passed
186	Test Case 5 (TC-001-3B)	12/1/2009	0	4	0	0	0	4	Passed
187	Test Case 6 (TC-001-3C)	12/1/2009	0	5	0	0	0	5	Passed
TC-002 -- Onboard Departure Tests									
188	Test Case 1 (TC-002-1A)	12/1/2009	0	18	0	0	0	18	Passed
189	Test Case 2 (TC-002-2)	12/1/2009	0	11	0	0	0	11	Passed
190	Test Case 3 (TC-002-3)	12/1/2009	0	15	0	0	0	15	Passed
TC-003 -- Onboard Train Activation Test									
191	Test Case 1 (TC-003-2A)	12/1/2009	12	11	0	0	1	24	Failed
TC-004 -- Onboard Train Consist Update Tests									
192	Test Case 1 (TC-004-1)	12/1/2009	0	12	1	0	0	13	Passed Conditionally
193	Test Case 2 (TC-004-2)	12/1/2009	0	12	1	0	0	13	Passed Conditionally
194	Test Case 3 (TC-004-3	12/1/2009	10	2	0	1	0	13	Failed
	Totals		941	4625	39	82	49	5736	

Test ID	System Test Procedure	Date Executed	NE	P	PC	F	BL	Total Steps	Test Status
TRNTERM-110 -- CAD Initiated Train Termination Requests									
178	Test Case 1	12/18/2009	0	19	0	0	0	19	Passed
179	Test Case 2	12/18/2009	16	5	0	0	0	21	Partial Test
TC-001 -- Onboard Power-On Tests									
182	Test Case 1 (TC-001-1A)	12/1/2009	0	6	0	0	0	6	Passed
184	Test Case 3 (TC-001-2)	12/1/2009	0	7	0	0	0	7	Passed
185	Test Case 4 (TC-001-3A)	12/1/2009	0	8	0	0	0	8	Passed
186	Test Case 5 (TC-001-3B)	12/1/2009	0	4	0	0	0	4	Passed
187	Test Case 6 (TC-001-3C)	12/1/2009	0	5	0	0	0	5	Passed
TC-002 -- Onboard Departure Tests									
188	Test Case 1 (TC-002-1A)	12/1/2009	0	18	0	0	0	18	Passed
189	Test Case 2 (TC-002-2)	12/1/2009	0	11	0	0	0	11	Passed
190	Test Case 3 (TC-002-3)	12/1/2009	0	15	0	0	0	15	Passed
TC-003 -- Onboard Train Activation Test									
191	Test Case 1 (TC-003-2A)	12/1/2009	12	11	0	0	1	24	Failed
TC-004 -- Onboard Train Consist Update Tests									
192	Test Case 1 (TC-004-1)	12/1/2009	0	12	1	0	0	13	Passed Conditionally
193	Test Case 2 (TC-004-2)	12/1/2009	0	12	1	0	0	13	Passed Conditionally
194	Test Case 3 (TC-004-3	12/1/2009	10	2	0	1	0	13	Failed
	Totals		941	4625	39	82	49	5736	

6.8 Builds 5–8 Testing – Reactive Enforcement of Speed and Authority Limits

The tests for Builds 5–8 occurred in November/December 2009. Testing goals were to perform testing of the Builds 5–8 functionality added in 2009 and to conduct a retest of earlier functionality with new server and onboard software.

The new software included:

- Initialization of V–PTC server and Onboard system
- V–PTC server/CAD initialization and synchronization
- Switch state awareness and remote switch control
- Display of train location
- Health status of Wayside and Onboard devices
- Train activation and termination
- Proceed Authority Issuance, Delivery, Rollup, Cancellation
- Following Move Authority Management (GCOR Line 9)
- Route Integrity Monitoring and Stop and Inspect Protection
- Reactive Enforcement and Train Termination

As a summary of the test plan, there were 250 requirements to be verified. A combination of laboratory and field testing was used to verify requirements. There were 54 total tests created with 215 test cases. The test cases included 45 that were laboratory-only, 63 that were field-only, and 107 that were both laboratory and field. There were also three fully operating scenario demonstrations.

An outline of the test approach appears below:

- Using the agreed to Requirements Verification Conditions and Criteria Matrix, LMC developed a test plan and test procedures to verify the V–PTC system requirements
- LMC conducted subsystem testing
    - Used developed subsystem tests to prove message interfaces and basic use case functionality
    - Onboard system used V–PTC server simulator
    - V–PTC server used Onboard simulator and RailComm CAD application
- LMC conducted system integration and test at the Manassas laboratory
    - Used wayside and CANAC simulators, and radio emulator
    - Connected Onboard system, RailComm CAD system and V–PTC server together in laboratory environment
    - Executed preliminary system tests against complete functionality strings
- TTCI/LCM field test team conducted preliminary LDS testing during week of Nov. 14, 2009
    - Changed out LCU on 2001
    - Upgraded software on 2001 and 203
    - Verified LDS navigation of the RTT, TTT, and sidings
- TTCI/LCM field test team started primary on-track testing on Nov. 30, 2009
    - Installed latest software and completed final integration with the target hardware
    - Worked through initial bugs and started formal system testing

Figure 28 shows the test setup used during Builds 5–8 testing.

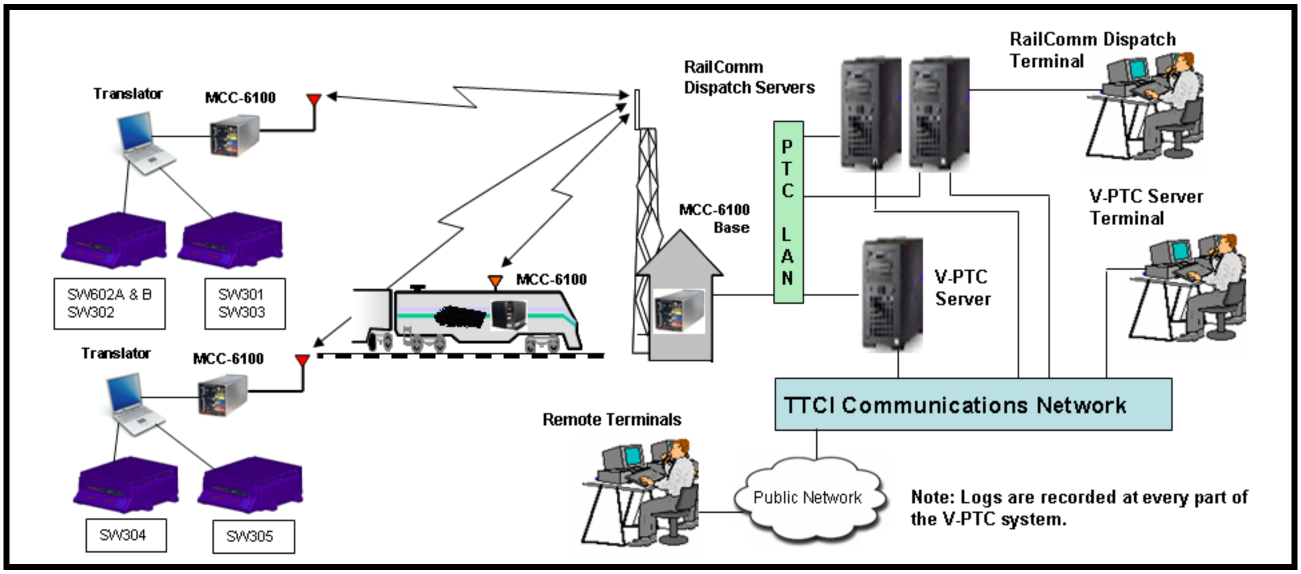

Figure 28. Test Setup for Builds 5–8 Testing

The individual system components that make up the test setup are described below:

1. RailComm's Dispatch System—used the DOC@TWC dispatching system modified to interface directly to the V–PTC Server on the PTC local area network.
2. Lockheed Martin's V–PTC Server—the central processing application used to vitally manage the safe operations of trains on the PTC territory.
3. Ansaldo STS's object controllers—the WIU provide remote control and status of switch points on the PTC territory.
4. LMC's onboard equipment—the LCU including the LDS and Train Control Component software applications, the LDU including the Train User Interface software application that displays the managed authority limits providing speed profiles, track line, alerts and warnings as the train operates on the controlled territory.
5. MeteorComm's MCC-6100 radios—provides the RF path for communications to remote devices at the waysides or on the trains.

6.9 Builds 5–8 Test Results

Detailed descriptions of the Builds 5–8 test results are contained in LMC's Builds 5–8 Test Report.[5] A summary of the report's content appears below.

In summary, 115 out of 167 tests passed completely without errors, another 10 tests passed conditionally, and 42 tests failed requirement-laden test steps during the formal test period and the post test verification. During Builds 5–8 testing, a total of 5,736 test steps were attempted, 4,625 test steps either executed properly or passed one or more requirements verifying check, 39 test steps passed conditionally, 82 test steps failed verification of one or more requirements, and 49 other test steps were blocked by an earlier failure. The remaining 941 test steps were not executed because the test was either not completed or the log file for the post test verification was not available for evaluation. See Table 8 for more details.

The following is a description of the fields included in Table 8.

- Date executed is the execution date of the test.
- The column labeled NE stands for not executed. This label is used for all test steps not executed during testing. Reasons include cases where two outcomes are possible depending on the timing of other actions in relationship to external stimulus.
- The column labeled P is the sum of nonrequirement and requirement-laden test steps.
- The column labeled PC stands for passed conditionally. This means the results obtained for the test step did not change the overall results of the test. For example, if the test was expecting a TS_DATA state change message as the next message, but the wayside device had to be reset. After the reset the TS_DATA message was received with the expected state, this test step was mark passed conditionally.
- The column labeled F stands for failed. This means the expected result did not happen.
- The column labeled BL stands for blocked. An earlier failure may block the execution of later steps. For example, an error causing a message to not be sent will cause a block of the acknowledgement message.
- The Total Steps column is a sum of test steps in columns NE, P, PC, F, and BL for each test case. This sum includes both the test case and the postanalysis test steps.

The Test Status column is the overall passed/failed test results. A Passed Conditionally means some aspect of the test failed, but the V–PTC system performance was not compromised by the failure.

Table 8. Builds 5–8 Test Case Results

Test ID	System Test Procedure	Date Executed	NE	P	PC	F	BL	Total Steps	Test Status
AUTH-0100 -- Authority Form Functional Test									
1	Test Case 1	12/6/2009	0	20	0	0	0	20	Passed
2	Test Case 2	12/6/2009	0	22	0	0	0	22	Passed
3	Test Case 3	12/6/2009	0	18	3	0	0	21	Passed Conditionally
4	Test Case 4	12/6/2009	0	20	0	0	0	20	Passed
5	Test Case 5	12/6/2009	0	20	1	1	0	22	Failed
6	Test Case 6	12/6/2009	0	23	0	0	0	23	Passed
7	Test Case 7	12/6/2009	0	23	0	0	0	23	Passed
8	Test Case 8	12/6/2009	0	23	0	0	0	23	Passed
9	Test Case 9	12/6/2009	0	24	0	0	0	24	Passed
AUTH-0200 -- Authority Management: Into and Out of Controlled Track									
10	Test Case 1	12/7/2009	0	34	1	2	0	37	Failed
AUTH-0300 -- Authority Management: Authority Rejection due to Data Issues									
16	Test Case 1	12/9/2009	0	9	1	0	0	10	Passed
17	Test Case 2	12/9/2009	14	8	0	0	0	22	Passed
18	Test Case 3	12/9/2009	17	13	0	0	0	30	Passed
19	Test Case 4	12/9/2009	15	12	0	0	0	27	Passed
20	Test Case 5	12/10/2009	3	12	0	0	0	15	Passed
21	Test Case 6	12/10/2009	0	11	0	0	0	11	Passed
22	Test Case 7	12/10/2009	0	11	0	0	0	11	Passed
23	Test Case 8	12/10/2009	0	11	0	0	0	11	Passed
AUTH-0400 -- Authority Management: Authority Rejection due to Invalid Limits									
24	Test Case 1	12/10/2009	0	10	0	0	0	10	Passed
25	Test Case 2	12/10/2009	0	10	0	0	0	10	Passed
26	Test Case 3	12/10/2009	0	11	0	0	0	11	Passed
27	Test Case 4	12/10/2009	0	8	2	3	0	13	Failed
28	Test Case 5	12/10/2009	0	10	2	1	0	13	Failed
29	Test Case 6	12/10/2009	0	10	2	1	0	13	Failed
30	Test Case 7	12/10/2009	0	9	2	1	0	12	Failed
AUTH-0500 -- Authority Management: Authority Rejection due to Functional Checks									
31	Test Case 1	12/10/2009	0	10	1	0	0	11	Passed
32	Test Case 2	12/10/2009	5	9	1	0	0	15	Passed
33	Test Case 3	12/10/2009	5	9	0	1	0	15	Passed Conditionally
34	Test Case 4	12/10/2009	5	9	0	1	0	15	Passed Conditionally
35	Test Case 5	12/10/2009	5	9	0	1	0	15	Passed Conditionally
AUTH-0600 -- Authority Management: Power Switch Alignment and Protection									
36	Test Case 1	12/15/2009	2	20	0	0	0	22	Passed
37	Test Case 2	12/15/2009	4	31	0	0	0	35	Passed
38	Test Case 3	12/15/2009	2	21	1	1	0	25	Failed
39	Test Case 4	12/15/2009	2	26	1	1	0	30	Failed
40	Test Case 7	12/17/2009	5	25	0	2	0	32	Failed
41	Test Case 8	12/17/2009	2	39	0	2	0	43	Failed
42	Test Case 9	12/17/2009	12	28	0	2	0	42	Failed
43	Test Case 10	12/17/2009	2	33	0	2	0	37	Failed
44	Test Case 11	12/17/2009	0	73	0	0	0	73	Passed
45	Test Case 12	12/17/2009	9	35	0	1	2	47	Failed
AUTH-0700 -- Authority Management: Hand-throw Switch Alignment and Protection									
46	Test Case 1	12/17/2009	12	0	2	0	1	15	Failed
47	Test Case 2	12/17/2009	17	4	4	0	1	26	Failed
48	Test Case 3	12/17/2009	2	25	0	0	0	27	Passed
49	Test Case 4	12/17/2009	1	17	0	2	7	27	Failed
50	Test Case 5	12/17/2009	9	24	0	0	0	33	Passed
51	Test Case 6	12/17/2009	2	24	0	0	0	26	Passed
AUTH-0800 -- Authority Management: Route Integrity, Apply & Release of Restriction(s)									
52	Test Case 1	12/8/2009	42	26	4	0	0	72	Passed
53	Test Case 2	12/8/2009	42	26	0	2	0	70	Failed
54	Test Case 3	12/8/2009	42	26	0	2	2	72	Failed
55	Test Case 4	12/8/2009	28	18	0	2	0	48	Failed
56	Test Case 5	12/8/2009	28	20	0	0	0	48	Passed
57	Test Case 6	12/8/2009	24	18	0	2	0	44	Failed
58	Test Case 7	12/8/2009	24	18	2	0	0	44	Passed Conditionally
59	Test Case 8	12/8/2009	2	6	0	1	0	9	Failed

Test ID	System Test Procedure	Date Executed	NE	P	PC	F	BL	Total Steps	Test Status
AUTH-1000 -- Authority Management: Route Integrity, Non-release of Restriction(s)									
60	Test Case 1	12/9/2009	12	34	2	2	0	50	Failed
61	Test Case 2	12/9/2009	12	67	0	0	0	79	Passed
62	Test Case 3	12/9/2009	12	67	0	0	0	79	Passed
63	Test Case 4	12/9/2009	12	67	0	0	0	79	Passed
64	Test Case 5	12/9/2009	42	63	0	0	0	105	Passed
65	Test Case 6	12/9/2009	63	39	0	0	0	102	Passed
66	Test Case 7	12/9/2009	63	39	0	0	0	102	Passed
67	Test Case 8	12/9/2009	20	14	2	2	0	38	Failed
68	Test Case 9	12/9/2009	30	23	0	4	0	57	Failed
69	Test Case 10	12/9/2009	30	27	0	0	0	57	Passed
70	Test Case 11	12/9/2009	33	40	0	0	0	73	Passed
71	Test Case 12	12/9/2009	22	20	0	0	0	42	Passed
AUTH-1100 -- Authority Management: Route Locking									
72	Test Case 1	12/11/2009	0	30	0	0	0	30	Passed
73	Test Case 2	12/11/2009	0	31	0	0	0	31	Passed
74	Test Case 3	12/11/2009	2	39	0	0	0	41	Passed
AUTH-1200 -- Authority Management: Safety Checking & Rejection, Part 1									
75	Test Case 1	11/18/2009	0	16	0	0	0	16	Passed
76	Test Case 2	11/18/2009	0	18	0	0	0	18	Passed
77	Test Case 3	11/18/2009	0	19	0	0	0	19	Passed
78	Test Case 4	11/18/2009	0	19	0	0	0	19	Passed
79	Test Case 5	11/18/2009	0	22	0	0	0	22	Passed
80	Test Case 6	11/18/2009	0	21	0	0	0	21	Passed
81	Test Case 7	11/18/2009	0	16	0	0	0	16	Passed
82	Test Case 8	11/18/2009	0	16	0	0	0	16	Passed
83	Test Case 9	11/18/2009	0	13	0	0	0	13	Passed
84	Test Case 10	11/18/2009	0	13	0	0	0	13	Passed
85	Test Case 11	11/18/2009	0	18	0	0	0	18	Passed
86	Test Case 12	11/21/2009	0	16	0	0	0	16	Passed
87	Test Case 13	11/18/2009	0	18	0	0	0	18	Passed
88	Test Case 14	11/18/2009	0	18	0	0	0	18	Passed
89	Test Case 15	11/18/2009	0	19	0	0	0	19	Passed
90	Test Case 16	11/18/2009	0	19	0	0	0	19	Passed
91	Test Case 17	11/18/2009	0	22	0	0	0	22	Passed
92	Test Case 18	11/18/2009	0	21	0	0	0	21	Passed
93	Test Case 19	11/18/2009	0	16	0	0	0	16	Passed
94	Test Case 20	11/18/2009	0	16	0	0	0	16	Passed
95	Test Case 21	11/21/2009	0	20	0	0	0	20	Passed
AUTH-1300 -- Authority Management: Automatic Rollup Verification									
96	Test Case 1	12/18/2009	0	13	0	0	0	13	Passed
97	Test Case 2	12/18/2009	0	18	0	0	0	18	Passed
98	Test Case 3	12/18/2009	0	19	0	2	0	21	Failed
99	Test Case 4	12/18/2009	0	20	0	0	0	20	Passed
100	Test Case 5	12/18/2009	0	16	0	0	0	16	Passed
101	Test Case 6	12/18/2009	0	30	0	1	0	31	Failed
AUTH-1400 -- Authority Management: Cancel and Re-issue Acceptance from Uncontrolled Track									
103	Test Case 1	12/17/2009	2	29	0	0	0	31	Passed
104	Test Case 2	12/17/2009	3	18	0	0	0	21	Passed
105	Test Case 3	12/17/2009	2	20	0	2	0	24	Failed
106	Test Case 4	12/17/2009	2	19	0	0	0	21	Passed
107	Test Case 5	12/17/2009	2	19	0	0	0	21	Passed
108	Test Case 6	12/17/2009	2	22	0	0	0	24	Passed
AUTH-1500 -- Authority Management: Cancel and Re-issue Acceptance on Controlled Track									
110	Test Case 2	12/17/2009	3	20	0	0	0	23	Passed
111	Test Case 3	12/17/2009	2	23	0	0	0	25	Passed
112	Test Case 4	12/17/2009	3	17	0	2	0	22	Failed
113	Test Case 5	12/17/2009	3	20	0	0	0	23	Passed
AUTH-1900 -- Authority Management: Cancel Authority Acceptance									
114	Test Case 1	12/18/2009	3	19	0	0	0	22	Passed
115	Test Case 2	12/18/2009	2	24	0	0	0	26	Passed
116	Test Case 3	12/18/2009	3	20	0	1	0	24	Failed
AUTH-2400 -- Authority Management: Conditional Authority, Following Move									
117	Test Case 1	12/18/2009	0	42	0	2	0	44	Failed
118	Test Case 2	12/18/2009	0	52	0	0	0	52	Passed
120	Test Case 4	12/18/2009	26	20	0	2	0	48	Failed

Test ID	System Test Procedure	Date Executed	NE	P	PC	F	BL	Total Steps	Test Status
CIVSPEED-100 -- Civil Speeds and Restrictions									
121	Test Case 1	12/6/2009	0	75	0	0	0	75	Passed
122	Test Case 2	12/5/2009	0	67	0	0	0	67	Passed
ENFORCE-100 -- Over-speed Enforcement Violations									
123	Test Case 1	12/12/2009	0	44	0	0	0	44	Passed
124	Test Case 2	12/10/2009	27	18	0	0	0	45	Passed
125	Test Case 3	12/10/2009	0	8	0	0	0	8	Passed
126	Test Case 4	12/10/2009	0	37	0	1	0	38	Failed
ENFORCE-110 -- Authority Limit Violations									
127	Test Case 1	12/12/2009	0	37	0	3	4	44	Failed
128	Test Case 2	12/12/2009	0	43	0	0	0	43	Passed
133	Test Case 7	12/12/2009	0	37	0	3	2	42	Failed
LOCMON-100 -- Location Determination Initialization Test									
140	Test Case 1	12/5/2009	0	59	0	2	0	61	Passed Conditionally
141	Test Case 2	12/5/2009	0	59	0	2	0	61	Passed Conditionally
142	Test Case 3	12/5/2009	3	58	0	4	2	67	Failed
143	Test Case 4	12/5/2009	4	61	0	2	0	67	Passed Conditionally
144	Test Case 5	12/5/2009	0	6	0	3	0	9	Failed
145	Test Case 6		22	7	0	0	1	30	Partial Test
LOCMON-110 -- Location Determination Initialization Test									
146	Test Case 1	12/5/2009	3	45	0	0	0	48	Passed
147	Test Case 2	12/5/2009	3	60	0	0	0	63	Passed
LOCMON-120 -- Location Determination Initialization Test									
148	Test Case 1	12/9/2009	0	42	0	0	0	42	Passed
149	Test Case 2	12/9/2009	6	43	0	1	0	50	Passed Conditionally
150	Test Case 3	12/9/2009	0	41	0	1	22	64	Failed
SWCNTL-100 -- Successful Control of Powered Switches									
151	Test Case 1	12/3/2009	4	98	0	0	0	102	Passed
152	Test Case 2	12/3/2009	0	93	0	0	0	93	Passed
153	Test Case 4	12/3/2009	4	89	0	0	0	93	Passed
154	Test Case 6	12/3/2009	0	206	0	0	0	206	Passed
SWCNTL-105 -- Hand-throw or Local Switch Alignment Changes									
155	Test Case 1	12/4/2009	0	33	0	0	0	33	Passed
156	Test Case 2	12/4/2009	0	165	0	0	0	165	Passed
SWCNTL-135 -- Communications Outages while Monitoring Switches									
157	Test Case 1	12/4/2009	4	64	0	0	0	68	Passed
158	Test Case 2	12/4/2009	2	33	0	0	0	35	Passed
159	Test Case 3	12/4/2009	2	35	0	0	0	37	Passed
160	Test Case 4	12/4/2009	4	61	0	0	0	65	Passed
161	Test Case 5	12/4/2009	2	34	0	0	0	36	Passed
SYSINIT-25 -- Initialization of the V-PTC Server and Onboard System									
162	Test Case 1	12/1/2009	0	9	0	0	0	9	Passed
163	Test Case 2	12/1/2009	0	19	0	2	0	21	Failed
164	Test Case 3	12/1/2009	0	9	0	2	0	11	Failed
166	Test Case 5	12/1/2009	1	15	0	0	0	16	Passed
167	Test Case 6	12/1/2009	0	32	0	0	0	32	Passed
168	Test Case 7	12/1/2009	3	3	0	1	4	11	Failed
SYSSYNC-50 -- Synchronization between the V-PTC Server and RailComm Dispatch System									
169	Test Case 1	11/20/2009	0	14	0	0	0	14	Passed
170	Test Case 2	11/20/2009	0	16	0	0	0	16	Passed
171	Test Case 3	11/20/2009	10	13	0	0	0	23	Passed
SYSSYNC-75 -- Synchronization between the V-PTC Server and RailComm Dispatch System									
172	Test Case 1	12/1/2009	4	19	0	0	0	23	Passed
173	Test Case 2	12/1/2009	0	25	0	0	0	25	Passed
TRNDISP-100 -- Location Determination Initialization									
174	Test Case 1	12/7/2009	0	58	3	0	0	61	Passed
175	Test Case 2	12/8/2009	0	13	0	0	0	13	Passed

Test ID	System Test Procedure	Date Executed	NE	P	PC	F	BL	Total Steps	Test Status
TRNTERM-110 -- CAD Initiated Train Termination Requests									
178	Test Case 1	12/18/2009	0	19	0	0	0	19	Passed
179	Test Case 2	12/18/2009	16	5	0	0	0	21	Partial Test
TC-001 -- Onboard Power-On Tests									
182	Test Case 1 (TC-001-1A)	12/1/2009	0	6	0	0	0	6	Passed
184	Test Case 3 (TC-001-2)	12/1/2009	0	7	0	0	0	7	Passed
185	Test Case 4 (TC-001-3A)	12/1/2009	0	8	0	0	0	8	Passed
186	Test Case 5 (TC-001-3B)	12/1/2009	0	4	0	0	0	4	Passed
187	Test Case 6 (TC-001-3C)	12/1/2009	0	5	0	0	0	5	Passed
TC-002 -- Onboard Departure Tests									
188	Test Case 1 (TC-002-1A)	12/1/2009	0	18	0	0	0	18	Passed
189	Test Case 2 (TC-002-2)	12/1/2009	0	11	0	0	0	11	Passed
190	Test Case 3 (TC-002-3)	12/1/2009	0	15	0	0	0	15	Passed
TC-003 -- Onboard Train Activation Test									
191	Test Case 1 (TC-003-2A)	12/1/2009	12	11	0	0	1	24	Failed
TC-004 -- Onboard Train Consist Update Tests									
192	Test Case 1 (TC-004-1)	12/1/2009	0	12	1	0	0	13	Passed Conditionally
193	Test Case 2 (TC-004-2)	12/1/2009	0	12	1	0	0	13	Passed Conditionally
194	Test Case 3 (TC-004-3	12/1/2009	10	2	0	1	0	13	Failed
	Totals		941	4625	39	82	49	5736	

During Builds 5–8 testing, a total of 82 test steps failed verification of one or more requirements. Because of the incremental nature of the deployment of the V–PTC system, most of the failures in this test period were the result of incomplete development on the software portions of the system. Overall, it appears that the development of the software is at a point approximately 80 percent of the way to allow for moving block functionality in the V–PTC system. With additional time and funding, it is likely that this functionality could become fully available.

7. Summary and Conclusions

TTCI, in cooperation with the FRA, RRF, and LMC, conducted R&D activities for a safety-critical, CBTC system. The system, functionally a second-generation PTC system, used an office-centric architecture based on current and evolving industry PTC communications technologies. The system R&D was performed under the V-PTC project, and the goal of the project was to build and test a fully functional vital PTC system that could be used in revenue service operations.

As part of this project, a PTC Test Bed was developed at TTC to support industry PTC development activities. The test bed consists of track and communications infrastructure, equipment for each major PTC segment, laboratory facilities, and specialized software tools capable of providing consistent and realistic test environments for PTC systems. The test bed's design enables multiple configurations, enabling users to mimic a desired test environment or scenario.

The V–PTC system was developed and tested in multiple incremental builds with increasing capabilities. This incremental development approach was made practical by using the closed track environment of the PTC Test Bed. It enabled the TTCI/LMC team to develop a system build, evaluate performance for that build, retest any scenarios that needed retesting, and continue on to the next build. This approach was influential in ensuring that development of a system of continually increasing complexity had a solid, well examined foundation on which to build and that each stage produced capabilities aligned with the SRS.

There were a number of lessons learned. At the highest level, the use of a dedicated test bed for this type of testing significantly increases the testing efficiency for developmental systems, freeing their testing from the constraints normally associated with revenue service operations. Also, the use of an incremental development and testing cycle is an excellent approach for developing complex systems. This approach produced a developmental system that showed constant progress with solid performing functionalities of increasingly complex capabilities. And finally, the results generated by this project show that the current state of PTC-related technologies is sufficient for developing and providing equipment for each of the major PTC segments, including Wayside, Locomotive, Back Office, and communications infrastructure.

A concluding recommendation is that when the industry's needs for moving block capabilities and/or a PTC office-centric architecture are sufficiently mature and necessary funds are available, the V–PTC project should be reactivated using updated SRS requirements that reflect current industry requirements.

8. References*

1. Locomotive Control Unit (LCU II) Performance Assessment V–PTC Server Location Report Process and Archiving–Final Report–Build 1
2. V–PTC Switch Monitoring Test Report–Build 2
3. V–PTC Switch Awareness Test Report–Build 3
4. V–PTC Switch Control Testing–Final Test Report–Build 4
5. V–PTC Authority Management Testing–Final Test Report–Builds 5-8
6. Concept of Operations for Vital PTC System in Unsignaled Territory
7. V–PTC System Requirements Specification (Revision 06)
8. V–PTC Onboard Train Internal System Architecture Document
9. V–PTC Field Testing at TTCI–Build 1

*[Please contact TTCI at (719) 584-0750 to obtain copies of these reports.]

Abbreviations and Acronyms

AAR	Association of American Railroads
AMS	Authority Management Server
ATCS	advanced train control system
BIU	brake interface unit
BOS	back office server
CAD	computer-aided dispatch
CBTC	communications-based train control
CFR	Code of Federal Regulations
CRC	cyclical redundancy checks
CCW	counterclockwise
CW	clockwise
DC	direct current
EBA	enforcement braking algorithm
FRA	Federal Railroad Administration
GPS	global positioning system
IDOT	Illinois Department of Transportation
LAN	local area network
LCM	local control mode
LCU	locomotive control unit
LDS	location determination system
LDU	locomotive display unit
LMC	Lockheed Martin Corporation
MHz	megahertz
mph	miles per hour
MS2	mission systems and sensors
NAJPTC	North American Joint Positive Train Control
PTC	positive train control
RF	radio frequency
RRF	Railroad Research Foundation
RSIA ‘08	Rail Safety Improvement Act of 2008

RTC	rail traffic controller
RTT	railroad test track
SRS	system requirements specification
TOES	train operations and energy simulator
TTC	Transportation Technology Center, the site
TTCI	Transportation Technology Center, Inc., the company
TTT	Transit Test Track
UTC	coordinated universal time
V–PTC	vital-positive train control
WIU	wayside interface unit