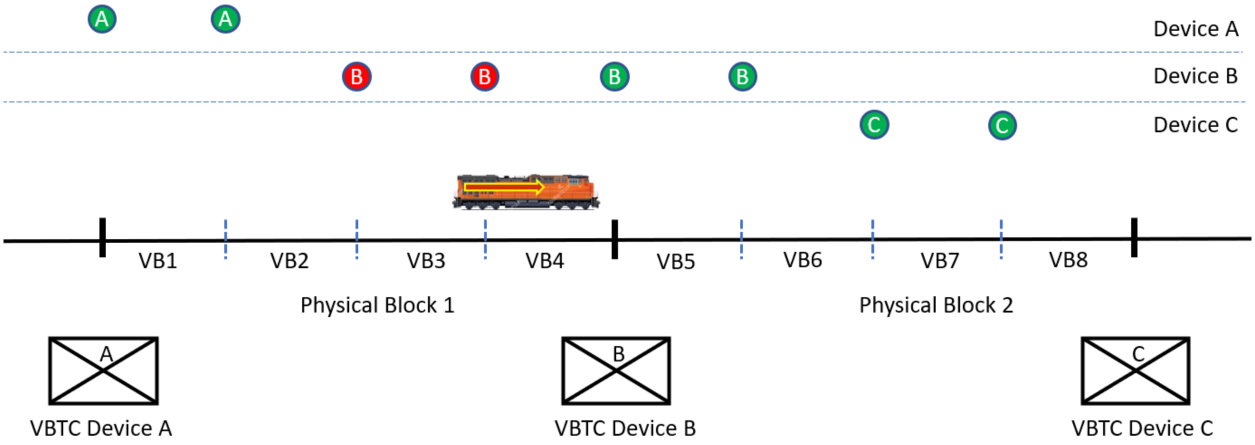
U.S. Department
of Transportation
**Federal Railroad
Administration**

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

Virtual Block Track Circuit Assessment Report



DOT/FRA/ORD-23/41

Final Report | December 2023

REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. REPORT DATE *(DD-MM-YYYY*
30/09/2022

2. REPORT TYPE
Technical Report

3. DATES COVERED *(From - To)*
06/2022 – 09/2022

4. TITLE AND SUBTITLE
Virtual Block Track Circuit Assessment Report

5a. CONTRACT NUMBER
DTFR5311D00008L

5b. GRANT NUMBER

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)
Xu Li – ORCID 0000-0003-2777-2214
Alan Polivka – ORCID 0000-0002-6424-5846
Mohamad Khater – ORCID 0000-0002-1288-9906
Matthew Holcomb – ORCID 0000-0001-7799-2202
Joel Kindt – ORCID 0000-0003-1248-982X

5d. PROJECT NUMBER

5e. TASK NUMBER
693JJ621F000018

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Transportation Technology Center, Inc.
55500 DOT Road
PO BOX 11130
Pueblo, CO 81001-0130

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Department of Transportation
Federal Railroad Administration
Office of Railroad Policy and Development
Office of Research, Development, and Technology (RD&T)
Washington, DC 20590

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)
DOT/FRA/ORD-23/41

12. DISTRIBUTION/AVAILABILITY STATEMENT
This document is available to the public through the FRA Web site at http://www.fra.dot.gov

13. SUPPLEMENTARY NOTES
COR: Francesco Bedini

14. ABSTRACT
Transportation Technology Center, Inc. (MxV Rail), in collaboration with a railroad technical advisory group (TAG), through Federal Railroad Administration (FRA)-funded research and proof-of-concept field testing with a supplier's equipment, found that a Virtual Block Track Circuit (VBTC) concept has the potential to reduce train headways and increase rail network capacity. The VBTC concept uses track circuit-based detection methods to divide conventional physical signal blocks into multiple virtual blocks, without adding wayside devices at virtual block boundaries or modifying the current Positive Train Control (PTC) onboard system.

15. SUBJECT TERMS
Virtual block track circuit, VBTC, Positive train control, PTC, Quasi-Moving block, QMB, Higher reliability and capacity train control, HRCTC, Virtual block

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			Xu Li, Senior Engineer
Unclassified	Unclassified	Unclassified		181	19b. TELEPHONE NUMBER *(Include area code)* 719-584-7121

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

METRIC/ENGLISH CONVERSION FACTORS

ENGLISH TO METRIC

LENGTH (APPROXIMATE)

1 inch (in) = 2.5 centimeters (cm)
1 foot (ft) = 30 centimeters (cm)
1 yard (yd) = 0.9 meter (m)
1 mile (mi) = 1.6 kilometers (km)

AREA (APPROXIMATE)

1 square inch (sq in, in^2) = 6.5 square centimeters (cm^2)
1 square foot (sq ft, ft^2) = 0.09 square meter (m^2)
1 square yard (sq yd, yd^2) = 0.8 square meter (m^2)
1 square mile (sq mi, mi^2) = 2.6 square kilometers (km^2)
1 acre = 0.4 hectare (he) = 4,000 square meters (m^2)

MASS - WEIGHT (APPROXIMATE)

1 ounce (oz) = 28 grams (gm)
1 pound (lb) = 0.45 kilogram (kg)
1 short ton = 2,000 pounds (lb) = 0.9 tonne (t)

VOLUME (APPROXIMATE)

1 teaspoon (tsp) = 5 milliliters (ml)
1 tablespoon (tbsp) = 15 milliliters (ml)
1 fluid ounce (fl oz) = 30 milliliters (ml)
1 cup (c) = 0.24 liter (l)
1 pint (pt) = 0.47 liter (l)
1 quart (qt) = 0.96 liter (l)
1 gallon (gal) = 3.8 liters (l)
1 cubic foot (cu ft, ft^3) = 0.03 cubic meter (m^3)
1 cubic yard (cu yd, yd^3) = 0.76 cubic meter (m^3)

TEMPERATURE (EXACT)

[(x-32)(5/9)] °F = y °C

METRIC TO ENGLISH

LENGTH (APPROXIMATE)

1 millimeter (mm) = 0.04 inch (in)
1 centimeter (cm) = 0.4 inch (in)
1 meter (m) = 3.3 feet (ft)
1 meter (m) = 1.1 yards (yd)
1 kilometer (km) = 0.6 mile (mi)

AREA (APPROXIMATE)

1 square centimeter (cm^2) = 0.16 square inch (sq in, in^2)
1 square meter (m^2) = 1.2 square yards (sq yd, yd^2)
1 square kilometer (km^2) = 0.4 square mile (sq mi, mi^2)
10,000 square meters (m^2) = 1 hectare (ha) = 2.5 acres

MASS - WEIGHT (APPROXIMATE)

1 gram (gm) = 0.036 ounce (oz)
1 kilogram (kg) = 2.2 pounds (lb)
1 tonne (t) = 1,000 kilograms (kg)
= 1.1 short tons

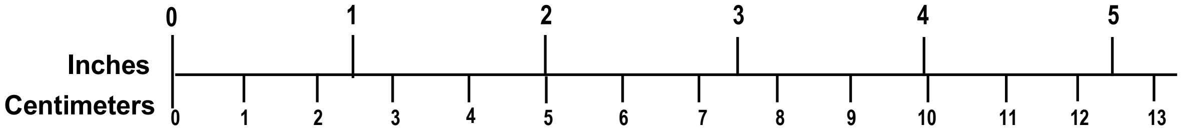
VOLUME (APPROXIMATE)

1 milliliter (ml) = 0.03 fluid ounce (fl oz)
1 liter (l) = 2.1 pints (pt)
1 liter (l) = 1.06 quarts (qt)
1 liter (l) = 0.26 gallon (gal)
1 cubic meter (m^3) = 36 cubic feet (cu ft, ft^3)
1 cubic meter (m^3) = 1.3 cubic yards (cu yd, yd^3)

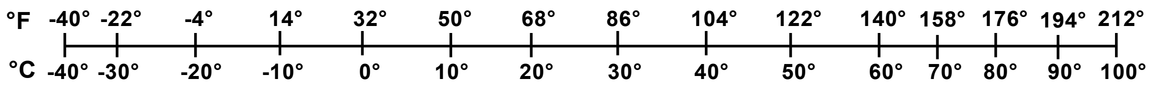
TEMPERATURE (EXACT)

[(9/5) y + 32] °C = x °F

QUICK INCH - CENTIMETER LENGTH CONVERSION



QUICK FAHRENHEIT - CELSIUS TEMPERATURE CONVERSIO



For more exact and or other conversion factors, see NIST Miscellaneous Publication 286, Units of Weights and Measures. Price $2.50 SD Catalog No. C13 10286

Updated 6/17/98

Acknowledgements

The authors acknowledge the support of the Association of American Railroads Train Control, Communications, and Operations committee and the members of the project technical advisory group for their support of this project.

Contents

Illustrations

Tables

Executive Summary

The Federal Railroad Administration (FRA) sponsored Transportation Technology Center, Inc. (MxV Rail), in collaboration with a railroad technical advisory group (TAG), to research and conduct proof-of-concept field testing of a Virtual Block Track Circuit (VBTC) concept. The VBTC concept uses track circuit-based detection methods to divide conventional physical signal blocks into multiple virtual blocks, without adding wayside devices at virtual block boundaries or modifying the current Positive Train Control (PTC) onboard system. The team conducted research and field studies using a supplier's product at the Transportation Technology Center (TTC) located in Pueblo, Colorado, from June to September 2022. Researchers concluded that VBTC has the potential to reduce train headways and increase rail network capacity.

Researchers focused on VBTC's high-level system characteristics and proposed a basic VBTC architecture and potential implementation within the current Interoperable Train Control (ITC) PTC system and the future Quasi-Moving Block (QMB) train control concept. In addition, the team identified some system characteristics and some potential limitations based on the proposed architecture. Researchers also conducted a capacity analysis that focused on efficiency improvements in ideal conditions.

Testing with the supplier's equipment not only provided an opportunity to evaluate the feasibility of the VBTC concept, but also provided an opportunity for a practical evaluation of the supplier's equipment. The field test focused on the performance of the system under basic train movement scenarios, operational scenarios with simulated rail conditions (e.g., broken rails and loss of shunt), and wet track scenarios. The team developed multiple test cases that considered a variety of issues that can affect the operation of the system. The devices that were tested performed essential VBTC functions, which demonstrated the potential of VBTC to help reduce train headways and increase the network traffic capacity under the various common operational scenarios tested. However, because of limited testing in wet track conditions, it was not possible to fully characterize the response of the devices in these conditions, so the team recommends additional study. Future research in this area should focus on the development of standard requirements for the VBTC system and additional field testing under a broader range of operational, physical, and environmental conditions.

1. Introduction

The Federal Railroad Administration (FRA) sponsored the Transportation Technology Center, Inc. (MxV Rail), with support from a railroad technical advisory group (TAG) and Alstom Corporation, to research and assess the Virtual Block Track Circuit (VBTC) concept. This project focused on researching the VBTC concept, evaluating the feasibility of implementing the concept within Interoperable Train Control (ITC), Positive Train Control (PTC), and Quasi-Moving Block (QMB) methods of operation, and demonstrating the concept using a supplier's product. Field testing was conducted at the Transportation Technology Center (TTC) located in Pueblo, Colorado, from June to September 2022.

1.1 Background

With the wide-scale implementation of PTC, the railroad industry is now looking for new methods to reduce train headways and improve line-of-road capacity without requiring significant modifications to the PTC architecture. One of the systems in which the industry has expressed considerable interest is VBTC.

The VBTC concept is a method that divides a physical track circuit block into multiple virtual blocks without adding wayside devices at each virtual block boundary. Each virtual block created is intended to perform a train control support function like that of a physical track block, but with certain limitations. Each known virtual block solution has limitations that prevent it from achieving the same performance advantages as shorter physical track circuits of the same length as the virtual blocks. There are multiple ways to improve various aspects of virtual block performance; the concept researched for this study is just one approach based on a specific type of existing VBTC-based system.

The VBTC system is based on a foundation of pulsed Direct Current (DC)-coded track circuits. The critical function of the VBTC system is to analyze the transmission current sent out from a VBTC transceiver and calculate the distance from that device to the closest shunting item. With this method, the system can create several location-based virtual boundaries and detect the location of the shunting item (e.g., a moving train).

Since the VBTC solution shares a similar foundation to DC-coded track circuits, some system-level drawbacks (e.g., the inability to detect the track block status between two shunting items within the same physical block) also occur with VBTC. The research team assessed these and other issues in this project. Some application-level suggestions to overcome some of the issues are provided in Appendix A.

1.2 Objectives

The objectives of this project are outlined below.

- Identify and analyze how the proposed VBTC concept could be integrated with and enhance the existing Overlay ITC PTC system and the QMB concept
- Analyze and/or model the performance of VBTC to estimate the potential capacity benefits when integrated with ITC PTC and QMB
- Assess the compatibility of VBTC with ITC PTC and QMB

- Perform tests on a VBTC prototype for functional and performance demonstration, test its ability to perform reliably under varying conditions and scenarios, and record and analyze the results
- Incorporate the observed results into the analysis to validate the final report conclusions regarding the potential benefits that this enhancement brings to train control operation and its degree of robustness

1.3 Overall Approach

The research team included a TAG composed of representatives of freight and passenger railroads. The general approach of this project was divided into three major steps.

The first step was to analyze how VBTC could be integrated with and enhance the existing Overlay ITC PTC system as well as the QMB system concept. The team generated a Concept of Operations (ConOps) document that included key performance needs and other details and prepared a list of system performance-related features to support the test plan development.

The second step was to develop plans for testing and installation, and to conduct field testing at TTC. The team developed a high-level test plan based on the generated feature list to guide the testing of the prototype. The plan identified all the conditions under which each feature would be tested, along with pass/fail criteria and the type of data to be gathered for each feature. Based on the high-level test plan and the installation characteristics, researchers developed a detailed field test plan for static and dynamic tests to demonstrate the functionality and performance of the VBTC concept based on the prototype. Data was collected and presented to the TAG for review.

The last step was to perform system-level capacity and compatibility assessments based on the field test results. The team then prepared this summary report to describe the methods used and to present the findings.

1.4 Scope

The scope of the project included 1) the development of the VBTC concept, 2) procurement of prototype equipment for demonstrating the concept, 3) testing of the prototype to demonstrate the feasibility of the concept, and 4) analysis of the potential benefits of the concept.

The scope did not include exhaustive verification testing of the concept or prototype, evaluation of the performance or reliability of the prototype, or safety analysis of the concept or prototype.

1.5 Organization of the Report

This summary report is organized as follows:

- Section 2 introduces the basic track circuit theory and simplified VBTC model.
- Section 3 presents the characteristics of the VBTC concept.
- Section 4 presents the proposed VBTC data and control architecture.
- Section 5 presents the potential implementation of the VBTC concept within the existing Overlay PTC system and QMB system concept.
- Section 6 describes the preparation of the field test and introduces the equipment used in the testing.

- Section 7 presents the test matrix and summary findings from the testing.
- Section 8 presents the capacity analysis for the VBTC concept compared with other train control systems.
- Section 9 presents conclusion and a project summary.
- Appendix A is the Concept of Operations for the VBTC.
- Appendix B is the field test report for the testing conducted during this project.
- Appendix C is the capacity analysis based on the concept and field test results.

2. Background and Overview of VBTC Concept

This section provides background information on track circuit theory and introduces the VBTC concept using a basic model. Further details on these topics can be found in Section 2 and Section 3 of Appendix A.

2.1 Basic Track Circuit Theory

The conventional track circuit is an electrical circuit-based wayside system that is used to detect track occupancy and to monitor track integrity within a block defined by the locations of insulated joints (IJ). Track circuits were developed to provide the stimulus for automatic wayside signals, which in turn provide information about the status of monitored blocks to maintain safe separation between trains. PTC builds upon this infrastructure to enforce the rules of operation regarding wayside signal indications and track circuit status. The most basic conventional track circuit has four key components: 1) a track circuit relay, 2) a power source, 3) IJs, and 4) track circuit resistors.

Figure 1 shows a simplified diagram of this basic track circuit. The power source and the track circuit relay are located at opposite ends of the track circuit block. Based on the fail-safe principle, the track circuit relay normally is energized to detect train occupancy or loss of track integrity (i.e., a rail break). When the track is shunted by an effective shunt (0.06 Ohms or lower) or if track integrity is lost, the track relay is de-energized, indicating either that the track block is occupied, or the circuit is broken.

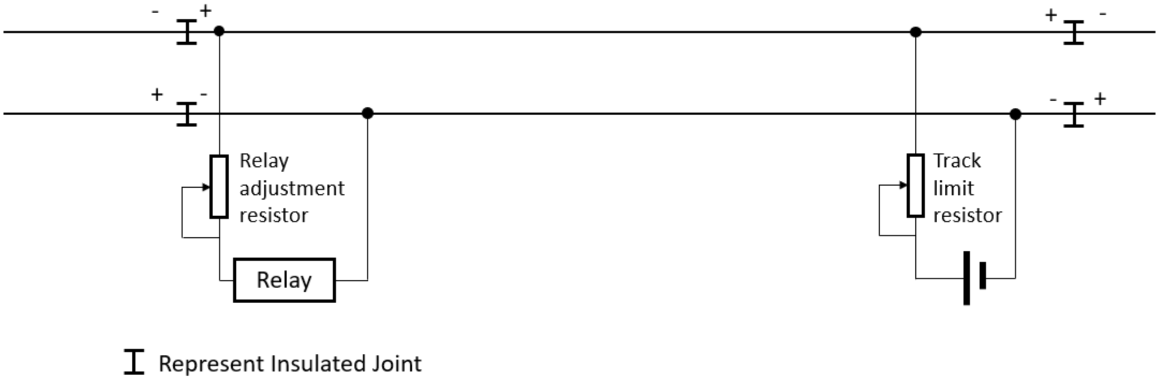


Figure 1. Conventional Track Circuit Model

As the technology has advanced, most conventional relay-based track circuits have been replaced with pulsed DC-coded track circuits.

Figure 2 presents a simplified diagram of a pulsed DC-coded track circuit where the track relay has been replaced with transceivers at both ends of the track. These transceivers work in coordination with each other on a synchronized time cycle. In each cycle, one transceiver transmits and the other one receives the pulsed DC codes. These coded pulses convey more information than would a relay-based DC track circuit. However, the coded track circuit is similar to the relay-based track circuit in that, when the track is shunted or when track integrity is diminished, the coded signal will not be received on the other end, which indicates either that the track is occupied, or the circuit is broken.

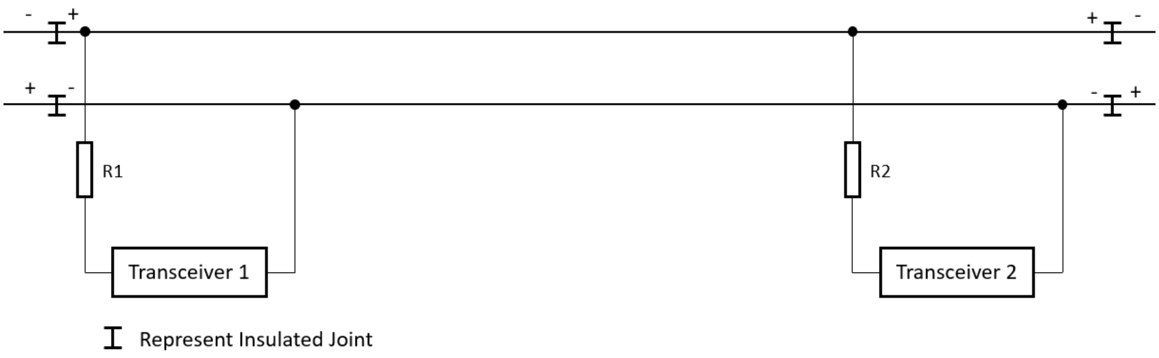


Figure 2. Pulsed DC-Coded Track Circuit Model

2.2 Simplified VBTC Model

Figure 3 illustrates the basic VBTC concept. In this simplified diagram, the physical block is divided into four virtual blocks (VBs) of equal length. The four blocks are identified in the diagram as VB1, VB2, VB3, and VB4. A pair of VBTC wayside devices, one at each end of the physical block (identified as VBTC devices A and B) function as transceivers that are coordinated by a synchronized time cycle and can measure both the transmit and receive currents. R1 and R2 represent the total “wayside” resistance at each VBTC device location.

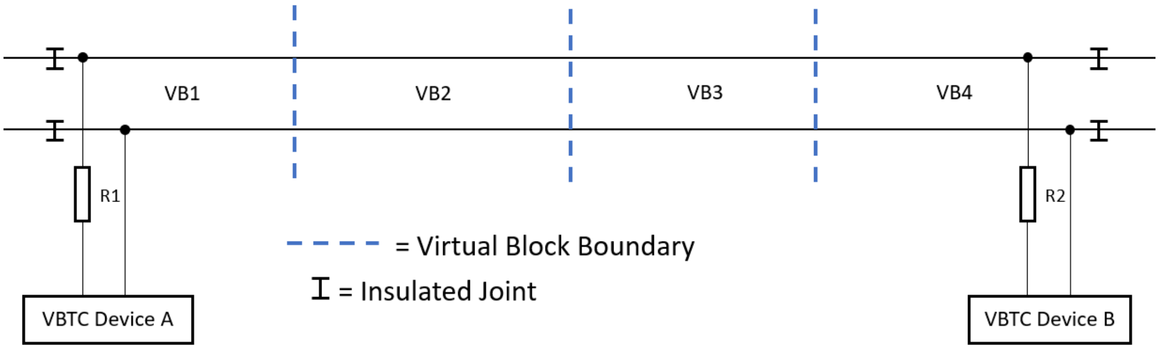


Figure 3. Simplified VBTC System Hardware Model

Figure 4 illustrates the transmit current (TxC) measured from VBTC Device A when a train enters the block from the side closest to VBTC Device A, travels at a constant speed through the block, and then exits from the block on the side closest to VBTC Device B. The T1 and T2 time points mark the moments when the first and last axles, respectively, enter the block. The End-of-Train (EOT) then proceeds through the block between times T2 and T3. The EOT location can be determined by the level of TxC current measured. The change in resistance from time T2 to time T3 is primarily the track rail resistance between the EOT and VBTC Device A. Thus, the rear end location of the train can be estimated using that measurement as well as other information collected (e.g., wayside resistance, track circuit output voltage, etc.)

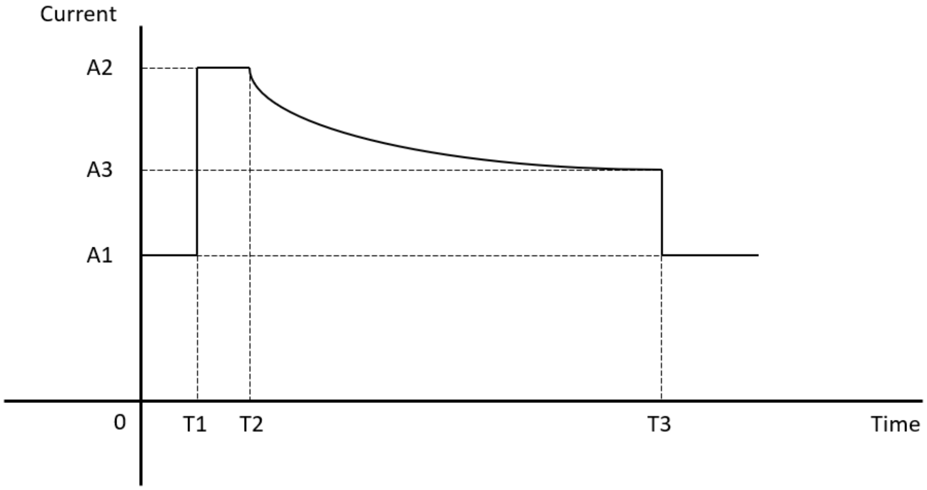


Figure 4. Transmit Current Measurement from VBTC Device

Locating the rear end of the train makes it possible for the system to determine when the train has cleared a VB within the full physical block. It also makes it possible to determine the integrity of the track through monitored transmit and receive currents. By conveying this information to a train as it approaches the physical block, it is possible to authorize movement of that train into the physical block and up through the last virtual block cleared by the leading train.

A detailed explanation of the VBTC principles is provided in Appendix A, Section 3.

3. VBTC Characteristics

This section introduces the characteristics of the VBTC concept. Further detail on this topic can be found in Appendix A, Section 4.

3.1 System Detected Occupancy vs. Actual Train Occupancy

Because it is a track circuit-based system, the VBTC concept presented in this document primarily uses measured transmit (Tx) current to locate a shunting item. Therefore, the system can only detect and calculate the distance between the VBTC wayside device at one side of a physical track circuit block and the closest shunting item within that block; anything beyond this shunting item is undetectable.

Figure 5 shows a train that is entirely inside VB3. Given the current loop limitation, VBTC Device A is only able to detect that the nearest shunting item (i.e., EOT) is located within VB3, and that VB1 and VB2 are Clear. The status of VB4 is undetectable from the VBTC Device A side. On the other side, VBTC Device B can detect only that a shunting item (i.e., the Head-of-Train (HOT)) is located within VB3 and that VB4 is Clear. The status of VB1 and VB2 are undetectable from the VBTC Device B side.

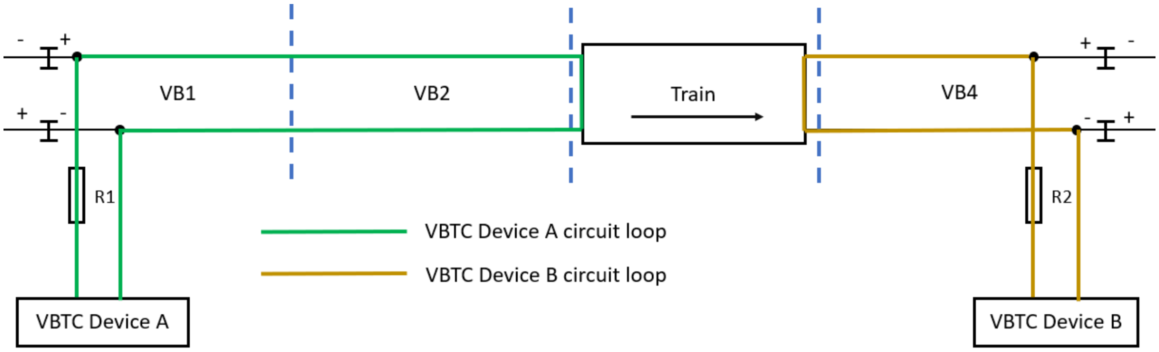


Figure 5. Occupancy Detection Example

3.2 Safety Buffer

The VBTC concept in this report depends on the measurement of the Tx current. Because environmental conditions and system resolution may affect the ability of this system to accurately detect occupancy of the virtual blocks, it is necessary to establish a buffer to ensure the safety of operations and avoid rear-end collisions due to inaccurate detection results. Figure 6 shows an example of one such safety buffer. Note that a virtual block is considered occupied if the safety buffer from an adjacent occupied block extends into it, as is the case with VB2 in Figure 6.

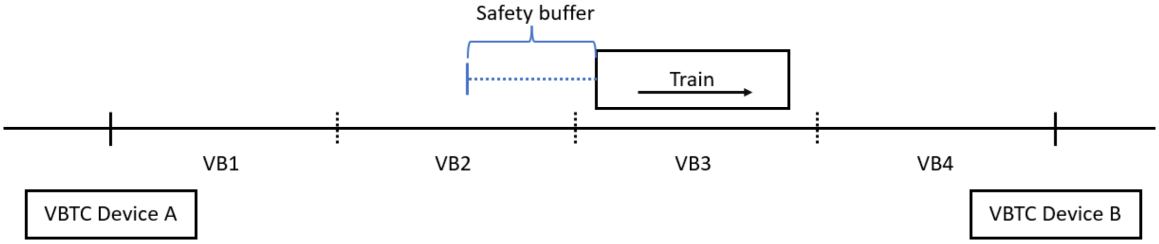


Figure 6. Example of Safety Buffer

3.3 Track Status Reaction Delay

DC-coded track circuits send a pulse every few seconds in both directions through each track block. Typically, due to safety requirements and to achieve the required robustness, track circuit systems will change track status to "less restrictive" only when at least two pulse transmission/detection cycles have confirmed that there has been a change in status. This dual confirmation pulse-cycle method creates a delay in reporting track clearance and, to a lesser extent, a delay in reporting track occupancy or rail break (which may or may not wait for a second pulse to confirm the transition). In turn, these delays result in a delay in determining train location that is proportional to the speed at which the train is moving. Although this phenomenon is traditionally associated with the relative occupancy status of a physical track circuit block, a similar effect (along with other location determination errors that will be discussed later) can also occur at VB boundaries.

3.4 Enter and Exit Detection Accuracy

The VBTC model presented in Section 2 is an ideal model. In an actual operational environment, there will be a distance gap between the exact shunting location and the VB boundary before occupancy or clearance can be detected, because of system hardware resolution and environmental conditions. This gap is referred to as the entry and exit accuracy of the VB.

Figure 7 shows an example of the entry accuracy of VB2 and the exit accuracy of VB1 for a train that is moving from left to right. In an actual operation environment, that accuracy will depend on various conditions even within the same VB and will directly affect the system performance.

Notice that, for a VB that has an IJ as one of its boundaries, the entry and exit accuracy related to the IJ boundary is considered close to zero.

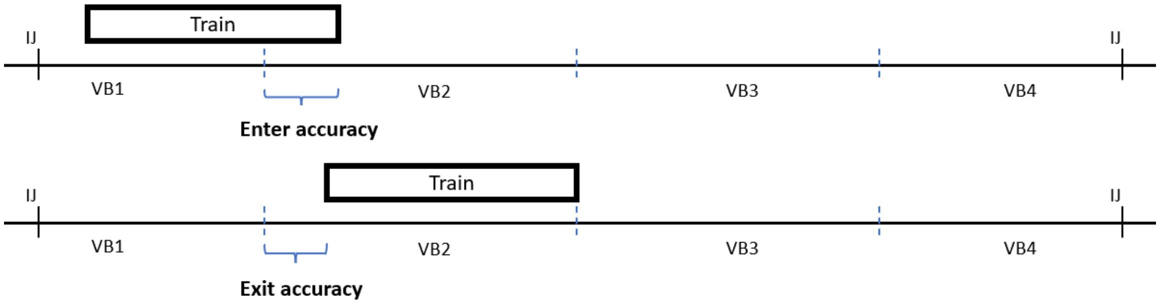


Figure 7. Virtual Block Entry and Exit Accuracy at the Boundary Between VB1 and VB2

4. VBTC Data Message and Wayside Behavior

This section describes how information is conveyed in the VBTC concept, based on the track status detected by a VBTC device. It also presents a potential VBTC implementation using the current ITC Wayside Status Message (WSM) architecture. Further detail on this topic can be found in Appendix A, Sections 5 and 6.

4.1 Information Conveyed by a VBTC Device

In an actual operational environment, a VBTC device would be installed near each physical block boundary location to gather the track circuit status of both adjacent blocks, as shown in Figure 8.

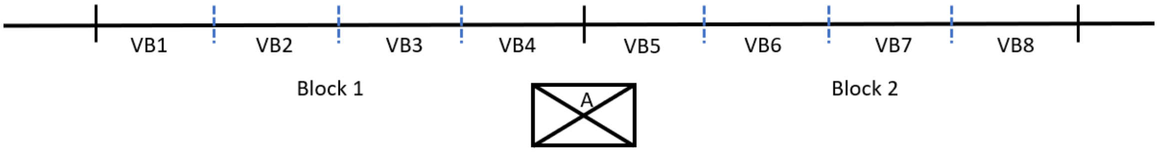


Figure 8. Illustration of VBTC Device and Detected Virtual Blocks from Adjacent Physical Blocks

A PTC-equipped train operating with its onboard in the ACTIVE state will respond to the wayside signal indications along its route. The status of the virtual blocks can be included as virtual signals in the WSMs from the Wayside Interface Units (WIUs) that broadcast the status of the physical blocks in the current ITC PTC system.

4.2 Inclusion of VBTC Information in WSMs

WSMs broadcast by the current ITC PTC system can be configured to include the VB device status generated by VBTC devices. The ITC PTC onboard segment does not distinguish between a virtual signal indication and a physical signal indication in a WSM.

The location of every virtual signal along a route must be added to the PTC track database for a train to be able to identify each virtual signal ahead of it, as has been done for physical signal locations to support ITC PTC operation.

Code (e.g., at the application level) must be included in VBTC devices so that the devices at both ends of a physical block will not simultaneously transmit status for the same virtual signal.

4.3 VBTC Signal Types and Aspects

In most cases, due to the short length of a typical VB, a three-aspect or four-aspect signal system would not be viable, as the train braking distance will often exceed one or two VB lengths. Thus, a VBTC virtual signal would typically be configured to indicate either Restricted (Signal Group 2) or Clear (Signal Group 5) aspects. One possible exception to this is when VBTC is deployed in a configuration to permit longer than usual physical blocks, rather than shorter blocks for reduced headways.

In the basic VBTC wayside architecture, each virtual signal is configured in the same way as a conventional physical signal. In an advanced, optional version of VBTC, each virtual signal is configured as an absolute, controlled signal, also referred to as a control point (CP). In this case, each virtual signal would normally be configured to indicate either Stop (Signal Group 1) or Clear (Signal Group 5) aspects. There are two benefits to this optional (i.e., Stop signal), advanced architecture:

1. When necessary, the dispatcher has more precise control over train movements. With conventional track circuits, the dispatcher can only control train movements to the level of a physical control point.
2. Using the VBTC signal as a controlled absolute signal, as opposed to an intermediate restricted signal, reduces the risk of collision due to the following train entering the occupied section under restricted speed.

The benefits of setting the virtual signals as absolute controllable signals are sometimes offset by the need for additional management by the dispatcher or CAD system. However, because the CPs should clear automatically when the VB they govern is clear, the dispatcher only needs to be involved if 1) the dispatcher does not want the CP to automatically clear and wants to hold the train back with more virtual block precision, or 2) the dispatcher wants to authorize the train to proceed into an occupied virtual block.

The implementation of CPs at virtual signals allows the use of conventional CAD-wayside communication (i.e., code line) protocols to communicate with the CAD system. The code line data load could increase substantially with the additional CPs.

The onboard segment uses track data and the location of a red signal to set up a Stop or Restricted Speed target, as appropriate.

4.4 Management of VBTC Signal Indications

A basic VBTC architecture (known as a single-layer VBTC concept), based on the system principles, characteristics, and the WSM implementation introduced in previous sections, is presented in this section, including explanations of how the PTC onboard segment uses the information delivered by the wayside devices, as well as the basic rules of system operation.

To further explain the basic VBTC system architecture, Figure 9 shows an example of a VBTC system with two physical track circuit blocks and three VBTC device sets. Each physical block contains four VBs of equal length. When there is no occupancy or rail break, each VBTC device will determine the (Clear) status of every virtual block within the two adjacent physical blocks. In this example, VBTC Devices A and B monitor the status of the four virtual blocks in Physical Block 1 and VBTC Devices B and C monitor the status of the four virtual blocks in Physical Block 2. Since the PTC system will not handle simultaneous WSMs from two different sources for the same virtual signal and direction of travel in the desired manner, the functionality must be implemented in the VBTC device application to determine which device will report on each of the VBs. The responsibility for reporting on each VBTC block may be assigned statically or (possibly) dynamically.

In the example shown in Figure 9, the train will be entering the track from VBTC Device A side and moving toward VBTC Device C. In Physical Block 1, VBTC Device A is at the entry side and VBTC Device B is at the exit side. In Physical Block 2, VBTC Device B is at the entry side and VBTC Device C is at the exit side. The diagram indicates which VBs have their status reported by each of the three VBTC devices. (For example, in the diagram VBTC Device A is reporting the status of VB1 and VB2.) This reflects one potential solution for a single-layer VBTC system, depicted here in terms of signals governing left-to-right train movement. (For simplicity, only the virtual signals that are within Physical Blocks 1 and 2 and are associated with the indicated direction-of-train movement are shown in the illustration.)

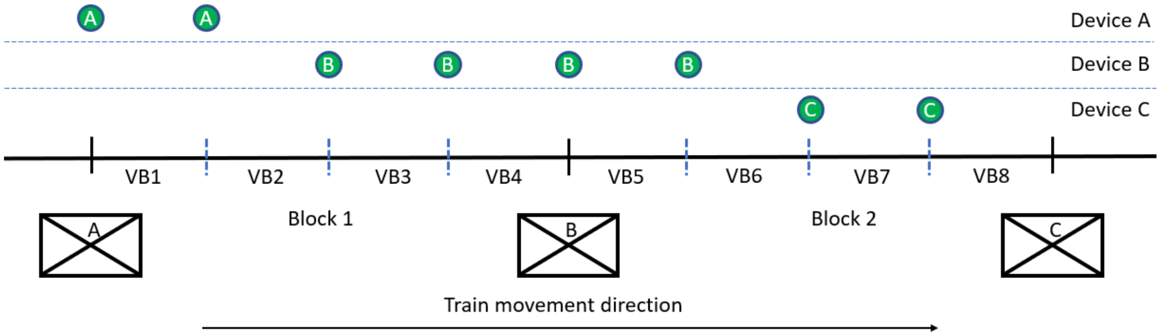


Figure 9. Example VBTC Setup Over Two Physical Blocks to Demonstrate Which VBs are Reported by Which VBTC Devices When No Train is Present

Table 1 presents the VB track status reported by each VBTC device as well as the actual train occupancy track status (i.e., "Actual Track Status").

Table 1. Single-Layer VBTC System Track Status Detection and Reporting Table Example

	VB1	VB2	VB3	VB4	VB5	VB6	VB7	VB8
Actual Track Status	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device A Detection Result	Clear	Clear	Clear	Clear	N/A	N/A	N/A	N/A
Device B Detection Result	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device C Detection Result	N/A	N/A	N/A	N/A	Clear	Clear	Clear	Clear
Reporting Device	A	A	B	B	B	B	C	C

The "Actual Track Status" row indicates the true state of whether each VB is occupied or clear. The "Device A Detection Result," "Device B Detection Result," and "Device C Detection Result" rows indicate the VB status information detected by each of the VBTC devices, and the "Reporting Device" row indicates an example of which VBTC device is providing the status of each VB.

The "single-layer" VBTC architecture is considered the basic VBTC system. This architecture is designed to operate with the ITC PTC onboard and the office segments "as is" (i.e., without requiring any modification of those segments to support VBTC operation). A train's ITC PTC onboard segment uses only the WSMs from the "incoming" signals (i.e., those ahead of it), whether they are virtual or physical, to determine the status of each block. The onboard segment monitors the WSMs that indicate the status of the VBs up to 5–8 miles ahead.

Since the current ITC PTC and future QMB onboard segments have a GPS-based location determination system as well as a track database, the onboard segment determines which virtual signal locations (or physical signals when not operating in VBTC territory) are ahead, and which signal locations have been passed by the front of the train.

Under a basic, single-layer VBTC system, the onboard segment has only one valid information source (of WSMs) assigned at any given time for the track status of each VB. Since each VB is monitored by two VBTC devices, those assignments may be configured statically, or they may change as occupancy and rail break conditions change. In dynamic solutions, these devices must include functionality (e.g., the railroad specific VBTC application code) to determine which device will be assigned to broadcast the WSMs for each VB.

For the purposes of the concept developed in this project, and assuming four VBs per physical block, the wayside information is provided based upon the following example rules for a static reporting assignment solution. However, a railroad may implement different algorithms in VBTC device application code, depending upon their specific needs.

1. When a physical block is unoccupied, application code in the VBTC devices will transmit the status of the two nearest VBs on either side of the IJ associated with that VBTC device.
2. The onboard location determination system is used by the ITC PTC onboard segment to determine where the front of the train is relative to each VB boundary, and in which direction the train is traveling, as the VB boundaries are stored in the track database.
3. Based on the front-of-train location, the direction-of-train movement, and the VB boundary locations in the track data associated with specific FeatureId's (i.e., virtual signals), the onboard segment uses the Device Status Code information in WSMs associated with the VBs ahead and discards the status information about virtual signals behind the front of the train.
4. Based on the front-of-train location, the direction-of-train movement, the signal locations in the track data (regardless of whether they are associated with a physical or virtual block boundary), and the train's onboard "horizon" limit (e.g., 5–8 miles), the onboard segment uses WSM information from whichever VBTC device is currently broadcasting the status for each VB within its horizon ahead. Track status received from any VBTC devices beyond the onboard segment's horizon is unnecessary and can be discarded by the onboard segment.
5. A direction stick is implemented with VBTC devices, as these devices need to understand the direction-of-train movement to apply the related current threshold (i.e., the entry or exit current threshold).
6. When an entry-side VBTC device detects a shunt within its assigned VBs that didn't originate at the IJ associated with that device, it will report the status of its assigned VB(s) up to that shunt, leaving the rest of its assigned VB(s) as Restricted until the VB(s) is (are) detectable.
7. If a VBTC device detects that a shunt is moving toward it, no safety buffer will be applied; otherwise, a safety buffer will be applied to protect the location uncertainty region behind the train.
8. When a train enters a physical block and passes over the IJ at the block's entrance, the entry-side VBTC device associated with that IJ is shunted so that it can no longer detect

the status of any VBs within the newly occupied physical block. When this situation is detected by the application code at that device, it transmits WSMs indicating that the VB the train just entered is not clear. The status of the next VB ahead of the train is based on its memory of the VB status prior to this event.

9. When an exit-side VBTC device detects an occupancy within its assigned VBs, it will indicate that the occupied VB, as well as a potential, undetectable VB beyond it, are not clear until those VBs are detected to be clear (i.e., the train exits the physical block).
10. When an entry-side VBTC device detects that a passing train has now cleared its associated IJ, it will report the VB status from the IJ to the shunting location (with a safety buffer) based on its detection results, while also reporting the status of the potential, undetectable VB beyond, based on its memory. The determination that the train has cleared the IJ can be based upon the fact that the device's transmit current into that block has dropped below a configured entry threshold. The state (i.e., memory) stick for this undetectable VB will be removed once the shunting item (e.g., a train with safety buffer) is considered past the boundary between this VB and the previous VB.
11. If the first VB had been reported as occupied by the entry side VBTC device (e.g., due to the leading train with safety buffer) when a new shunting item (e.g., a following train) enters from entry side IJ, then the entry side VBTC device should remove the state (i.e., memory) stick, which will result in all the VBs assigned to the entry side VBTC device reporting as occupied until those blocks can be detected as unoccupied.

Application code must also address less frequent situations, such as determining which device will transmit WSMs for each VB when a train changes directions within a physical block.

Several detailed example scenarios about applying the operation rules under this static reporting assignment solution can be found in the Appendix A, Section 6.

5. Implementation of VBTC Within Existing ITC PTC and Future QMB

This section introduces the potential implementation of VBTC within the current ITC PTC and future QMB environments. Further details on this topic can be found in Appendix A, Sections 7 and 8.

5.1 Implementation Within the ITC PTC System

To implement the VBTC concept within the current ITC PTC system, the following updates are required:

1. Track database update: Each VB location and track association must be included in the track database as if it were a physical signal. The position within the WSM where the VB status will appear for each facing direction also must be defined within the track data for each virtual signal unless each virtual signal is assigned its own WSM. Each virtual signal will convey only binary (i.e., two-aspect) status – namely, Signal Group 2 or 5 for intermediate/automatic signals and Signal Group 1 or 5 for controlled/absolute signals. No approach or absolute aspects are conveyed in VB operation.
2. PTC WIU updates: Where VBTC is deployed, each WIU's configuration will need to be updated to accept status for each VB within its associated physical block and to populate the status of all VBs associated with that WIU within its WSMs.

VBTC is designed to operate within the ITC PTC system without requiring modifications to the onboard and office segments.

5.2 Implementation Within the QMB System

VBTC may be integrated with the QMB method of train control.

5.2.1 VBTC Operations With QMB

In QMB, movement authorities, known as PTC Exclusive Authorities (PTCEA), are provided to the onboard segment. The onboard segment follows the more restrictive indication between the PTCEA and the signaling system, whether it is a conventional signaling system or a VBTC system. Basic QMB requires track circuits (for detecting rail breaks and unauthorized occupancies), but since it functions independently of those circuits, no additional integration is required with VBTC. The headways and traffic capacity limits under Basic QMB are determined by whatever track circuits are present. Therefore, the headway and traffic capacity benefits of VBTC are directly applicable to Basic QMB.

Note that if a QMB train is not equipped with vital rear-of-train location (VRTL), automatic QMB movement authority roll-ups will be based upon the estimated rear-of-train location, calculated from the front-of-train location and the assumed train-length information. The PTCEA provides some collision protection because the following train will be forced to a stop by its PTCEA limit. However, the PTCEA limit for the following train is based on the leading train's rolled-up PTCEA limit, which itself is determined by the estimated train length plus the QMB safety margin. Additional protection can be provided by instead configuring all virtual signals as absolute signals, with Stop (Signal Group 1) being their more restrictive state. This, however, would require dispatcher involvement whenever two trains needed to get closer to each other than one or two blocks. It could also involve configuring each virtual signal to be controllable by the CAD system as a CP. On the other hand, the CPs would provide dispatchers with finer resolution control over traffic.

5.2.2 Potential Modifications to Consider With Implementation of VBTC and QMB

A potential modification to the Basic QMB onboard segment could allow it to use the sub-track circuit granularity provided by VBTC. This would be useful in cases where a QMB train does not have a VRTL system, thus requiring a speed restriction behind it for a following train to operate in the same physical block. Once the QMB train has received input from the VBTC system that a VB behind the leading train is clear, the QMB train can roll up its PTCEA through that clear VB. To do this, a QMB train would need to consider the WSMs for the virtual blocks behind it, which would be an improvement over the current QMB ConOps and specifications.

Another potential modification to Basic QMB would be for the office segment to subscribe to WSMs and use that information to manage movement authorities. This could be helpful in cases where the onboard segment is not communicating with the back office, such as a Non-Enforcing or Non-Communicating (NENC) train. The office segment could roll up the movement authorities of a leading train based on the WSMs that indicate a clear VB behind the leading train. However, there is a challenge with this concept because the WSMs identify only the status of the block and not the train itself. Therefore, the QMB concept does not currently support using WSMs in this manner.

6. Field Test Setup

The setup of the field test is presented below, including a description of the test bed and train consists prepared for the test, as well as the VBTC equipment used.

The detailed content relating to this topic can be found in Appendix B.

6.1 Test Bed

The test bed for the field test used the Railroad Test Track (RTT) at the TTC located in Pueblo, Colorado. The RTT is a 13.5-mile test track with continuous welded rail. The test section on the RTT selected for this field test is between posts R40.5 and R64.5, with 6,000-foot entry track sections on either side of the test section.

The VBTC test track was divided into two physical blocks, with each block 11,880 feet long. The bungalow located at R52 was equipped with one set of VBTC devices; the bungalows located at R40 and R64 were each equipped with one set of VBTC devices and one set of entry track circuit (not VBTC). The GPS coordinates were measured for each key location and for the ideal VB boundaries.

The VBTC test track layout is shown in Figure 10.

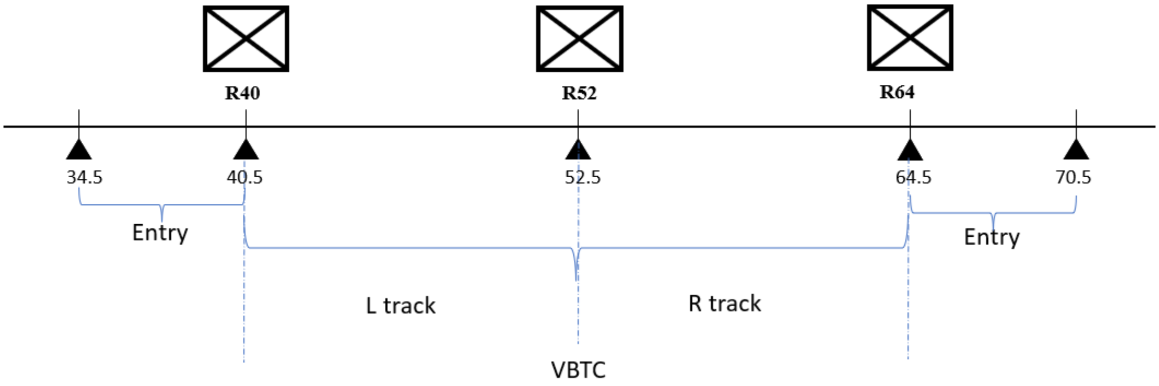


Figure 10. VBTC Test Track Layout

For the test cases where a broken rail was required, a mechanism to simulate the broken rail environment was set up at R46. For normal test scenarios, a jumper bond was welded across the R46 IJ. As per the requirements for broken-rail tests, the mechanism was triggered in real time as a train passed over R46 to simulate a rail break under a train (the most common situation in which a rail break occurs). The rail break mechanism consisted of a clamp applied across a cut in the middle of the jumper wire. A rope attached to the clamp enabled a team member to pull on the rope to remove the clamp and cause a rail discontinuity (i.e., break) from a safe distance as the train passed over R46. Other options, such as a relay, were considered to create a precisely timed rail break event, but these options presented too much resistance given the sensitivity of the track circuit. The mechanism used for this testing maintained much the same track circuit resistance as before the mechanism was introduced.

6.2 Test Train Consist

Most of the VBTC tests were performed with a train that consisted of a single locomotive and nine freight rail cars (six loaded and three unloaded). The length from the first axle of the locomotive to the last axle of the last rail car was 503 feet. In addition, a GPS device was installed on the locomotive to measure real-time GPS location data. A diagram and photo of the train consist are shown in Figure 11 and Figure 12, respectively.

Figure 11. GPS Location Within the Train Consist

Figure 12. Train Consist Used for Testing

6.3 Alstom ElectroLogIXS/EC5 Device and Application Code

The equipment selected for the testing in this project is based on the Alstom ElectroLogIXS/EC5 system, a DC-coded track circuit system that is widely used within the industry. In addition, the latest component VTI-2E module was installed within the chassis to measure the transmit (Tx) current and receive (Rx) current, and to provide the VBTC functions.

Application code, with the minimum functionality required to support testing of the VBTC concept within the test environment, was provided by Alstom.

The application code for the testing had the following characteristics, based on the test needs:

- Track code: basic track codes to be used to indicate track occupancy status and set up direction for train movement

- Direction stick: used for setting up the direction of movement based on the track code from the adjacent track section or entry track circuit
- Track status: used to indicate the VB occupancy status for each individual VB after the system is fully calibrated, as well as the occupancy status for the whole physical block
- VB mode status: used for indicating when the VB mode is active or inactive for each train movement
- Broken rail indication: used for showing the track integrity status

6.4 Data Recording Methods

The field test data was recorded using the following methods:

- ElectroLogIXS/EC5 data log and system log: The vital system events were recorded in the ElectroLogIXS/EC5 system log, and all status changes were recorded in the ElectroLogIXS/EC5 data log; all logs were time stamped and set to UTC time.
- Wayside System Data Management Module and Grafana: Based on the test needs, a wayside system data management module (WSDMM) was added to the ElectroLogIXS/EC5 device to obtain and record the Tx current and receive current for each device. The data collected was visualized in Grafana – a multi-platform, open-source analytics and interactive visualization web application.
- GPS data: A GPS device was installed on the test train at the HOT location and GPS data was recorded for some test cases, based on the test needs.

6.5 Calibration Process

Before the VB mode can be activated, every ElectroLogIXS/EC5-based VBTC device must be calibrated by running 50 valid train movements through the monitored physical block. Each device is calibrated independently, resulting in a calibration curve that is unique for each side of a physical block.

To be considered a valid calibration train movement (according to the manual received from the supplier) the following requirements nust be satisfied:

- A through move
- The average speed of the complete move across the entire track circuit must be greater than 15 mph
- No stopping or reversing
- Minimal acceleration (decelerating or constant speed trains are also valid, as are trains with limited acceleration)

When a train completes a movement in a VBTC track section and fully exits a physical track circuit block, the system log provides the analysis result, indicating whether the train movement was valid.

6.6 Limited Field Testing Conditions and Supplier Adjustment Factor

The field testing was limited to a train consist with nine cars and a single locomotive, which meant that there was limited variation in the calibration process. A calibration process with limited variation means that there will be a narrower range of operational variation in VBTC devices (e.g., the system thresholds for VBTC operation are not wide enough to tolerate greater variances in conditions). This can result in the system exiting VB mode more often.

A user may adjust the supplier's parameter (known as the "VB Scale Factor"). While increasing this parameter allows for widening the allowable operational variance for VB mode, it also increases the VB safety buffer, which affects the potential capacity gain when using VBTC.

7. Test Matrix and Test Results

This section provides a summary of the test cases and the corresponding test results.

7.1 Test Matrix

Table 2 shows the test cases, a brief description of each test case, and the test group to which each test case belongs. Detailed test procedures and test results can be found in Appendix B, Section 6.

Table 2. Test Case Matrix

Test No.	Test group	Test case name	Test case description
1	Basic performance test	Basic system operation test	Basic constant movement
2	Basic performance test	System detection accuracy under same VB Scale Factor	Basic constant movement at various speeds under same VB Scale Factor
3	Basic performance test	System detection accuracy under different VB Scale Factors	Basic constant movement with various VB Scale Factors
4	Basic performance test	Changing speed test	Acceleration test within VBTC section
5	Operational scenario test	Single locomotive test	Single locomotive constant speed test
6	Operational scenario test	Pull-apart test	An operational pull apart scenario (train was decoupled in the middle)
7	Operational scenario test	Double occupancy within single block test	A double occupancy event within same physical block
8	Operational scenario test	Changing movement direction within single block	A movement direction change event in operational scenario within same physical block
9	Operational scenario test	Broken rail test with multiple scenarios	Broken rail test with different scenarios including broken rail caused by train and spontaneous broken rail
10	Operational scenario test	Power outage test	A field power outage event to verify system performance
11	Operational scenario test	Loss of shunt test due to simulated rusty surface test	Simulate rusty surface within middle of block and a loss of shunt event
12	Wet track test	Wet track preparation	Preparation for wet track by distributing water from tank car; Data was collected during the train movement
13	Wet track test	Constant speed test	Basic constant movement test with wet track
14	Wet track test	Broken rail test	Broken rail test with different scenarios under wet track similar to test case 9
15	Wet track test	Ballast condition test	Test ballast condition change with track from wet to dry

7.2 Basic System Performance

The ElectroLogIXS/EC5 device with VBTC functionality that was tested on this project performed essential VBTC concept functions under several typical operational scenarios. This was seen by observing VB system status changes in the basic performance test cases (Test No. 1 to No. 4) shown in the test case matrix (i.e., the clear/not clear changes recorded in time-stamped logs for each VB occurred at the appropriate times). The detailed test results can be found in Appendix B, Section 6. Scenarios tested include constant speed movement, changing movement direction within a single physical block, pull-apart protection, double occupancy within a single physical block, and power outage.

In the scenarios involving train acceleration within a physical block, two occurrences of the system exiting the VB mode were observed. In each of these occurrences, the VBTC system exited the VB mode and operated under conventional physical block mode. The reasons for exiting the VB mode were recorded in the system data log as follows:

- The reason for the first occurrence was logged as “Location Disabled; Far Entry Threshold Not Met.” The manual indicates this means the threshold check failed shortly after the train entered the block.
- The reason for the second occurrence was logged as “Location Disabled; Bad Signal Quality.” According to the manual, this VB mode failure was caused by a “Signal Quality fault detected (due to rapid decrease in Tx current) for an Outbound train.”

7.3 VB Scale Factor Related Performance

As previously described, the VB Scale Factor directly affects the system capacity performance, so several test cases were performed to characterize these performance impacts. During the VB Scale Factor related test cases (Tests No. 2 and No. 3), the team made the following observations:

1. The higher the speed-of-train movement, the more impact a delay in detecting the track block status will have. This is because the status of a VB that is transitioning from Occupied to Clear will be delayed by the combination of the safety buffer, the system-processing time, and the de-bounce buffer (a function used to eliminate the effects of an erratic signal). This was observed by comparing the log of the GPS train location with the log of the VB status, both of which are time-stamped.
2. Increasing the VB Scale Factor can decrease the accuracy of the VB status detection. When the VB Scale Factor was increased from 50 percent to 255 percent, a significant increase was observed in the distance between the EOT to the ideal VB boundary related to that status (when the virtual block track status changed). This translates into excess headway for a following train.
3. When the VB Scale Factor is set to 255 percent, the detection inaccuracy can be longer than a VB length. The team also observed that no VBs were reported Clear by a device until the train exited the physical block, even though the VBTC system log showed that this device was still running under VB mode. Then, all VB status within the physical block from this device reported Clear at the same time.

7.4 System Performance Under Different Ballast Conditions

The ElectroLogIXS/EC5 device with VBTC functionality was tested under different ballast conditions (e.g., wet track test cases compared to similar cases under dry conditions) and the team observed the following findings:

1. During the calibration process, a calibration train movement has a higher chance of being considered invalid during or shortly after rainy weather, when track conditions are wet.
2. During the test process, after the system was fully calibrated, the system failed the Threshold check (which led to the system deactivating VB mode) more often for train movements over track which had recently incurred a significant condition change (i.e., from dry to wet). The threshold check is a VBTC function that runs every time a train enters a physical block to determine if the first few Tx current pulses measured are within calibrated limits for VB mode to be active. Deactivating VB mode is expected behavior and impacts the potential capacity gains but does not affect operational safety. The supplier indicated that the ElectroLogIXS/EC5 device with VBTC functionality has a method for adapting to changing conditions by continuously updating the system calibration so that these operational impacts are only temporary.

Further testing with higher moisture levels is recommended to analyze the performance under wet track conditions. Setting the VB Scale Factor to a higher value in locations that experience more rain may help relieve this problem at the cost of reducing capacity gain.

7.5 Broken Rail Detection and Non-Vital Broken Rail Location Report

Broken rail test cases (Tests No. 9 and No. 14) were used to evaluate the system performance in detecting a rail break within an occupied block and were also used to evaluate the accuracy of location reporting under various conditions. During those tests, a rail break was simulated several times by disconnecting and then later reconnecting a jumper wire across an insulated joint in the middle of a selected track circuit block (detailed information can be found in Appendix B, Section 3). The ElectroLogIXS/EC5 devices with VBTC functionality tested were shown to be capable of detecting the simulated rail break between this VBTC device and an occupancy (i.e., Train) within the same physical block. They also proactively exited VB mode, which was expected to protect operational safety. The system was also shown to detect a rail break under the wet track conditions created for the field test.

The location of a rail break is non-vital information that is recorded in the system log. This location information is only valid in the case of a rail break that has occurred under a train when the system was operating in VB mode, since it is based on the estimated shunting location at the moment the rail break is detected by the VBTC (i.e., when the train has just cleared the break). However, this location information cannot be used for vital purposes because of the risk of misreporting the location during a spontaneous rail-break scenario (i.e., a rail break that did not occur under the train). Further details on this topic are available in Appendix B, Sections 6.9 and 6.14.

7.6 Performance for Loss of Shunt Issue Due to Rusty Rail Surface

In Test No. 11, a loss-of-shunt scenario due to a simulated rusty rail surface was tested. For the outbound scenarios that were tested, the system exited VB mode with simulated rusty rail surface zones that were 1,500 feet and 2,500 feet long. Thus, the VBTC system offered protection in those scenarios.

7.7 Test Result Conclusion

In most test cases, the devices tested at TTC performed essential VBTC functions. Therefore, under common operational scenarios, VBTC can be expected to provide a means of reducing train headways and increasing the network traffic capacity. However, additional evaluation under a broader range of conditions, both operational and environmental, is recommended to fully evaluate the performance.

8. Capacity Analysis with VBTC

This project investigated train operation performance when VBTC is implemented in conjunction with Overlay PTC (O-PTC), Enhanced Overlay PTC (EO-PTC), or Basic QMB (B-QMB) train control methods. The performance of trains when using VBTC was compared with the use of conventional track circuits under the same train control methods, with EO-PTC configured with track circuits that had been split in half (i.e., half the length of the original track circuit) and Full Moving Block (FMB).

An analytical model was developed to calculate train headways based on Minimum Steady State Separation (Min SSS) between a pair of trains in an ideal following-move scenario (i.e., not a whole track or network). The analysis considered different train types, track speeds, track circuit lengths, and operating conditions. It also included latency or margins introduced by multiple system components during the operation of following train moves. Since the values for these margins can change based on the actual operating conditions, the results may change slightly under different conditions.

Under EO-PTC and B-QMB train control methods, trains entering an occupied block must be limited to Restricted Speed, as the rear-end of a leading train cannot be vitally determined, and conventional track circuits cannot detect broken rail in an occupied track circuit. To attain capacity improvement with EO-PTC and B-QMB, VBTC can be used to allow a train to enter an occupied block at Maximum Authorized Speed (MAS) under specific conditions. This is because VBTC can detect a broken rail between one end of the track circuit and a shunting axle of a train. Moreover, it can detect the rear-end location of a train with a Safety Buffer (SB) to indicate which VBs within the physical block are Occupied or Clear.

Although EO-PTC and B-QMB are distinct train control methods, they achieve the same Min SSS distance, assuming that PTCEA roll-ups in B-QMB are frequent enough compared with the time that it takes a train to release a block (i.e., physical block in the case of conventional track circuits and VB in the case of VBTC) to avoid adding a margin to train separation.

Table 3 shows the Min SSS for both EO-PTC and VBTC for a variety of train types, MAS, and track circuit length (TC_L). The headway reduction column in Table 3 shows the proportional reduction of train headway (affected by Min SSS) in EO-PTC when operating with VBTC, compared with EO-PTC when operating with conventional track circuits. This comparison was made to show the greater capacity gains that are possible for VBTC in comparison to conventional track circuits when using the EO-PTC train control method. Train headway reduction for freight trains is in the range of 12 to 30 percent depending on MAS and track circuit lengths. For expedited and passenger trains, headway reduction is in the range of 16 to 34 percent and 20 to 40 percent, respectively.

The overall results indicate that implementing VBTC under EO-PTC has the potential to significantly reduce train headway and help increase railroad network capacity and efficiency in areas where capacity is being reached during following move operations.

Appendix C contains further details about the capacity analysis.

Table 3. Headway Reductions That Can Lead to Capacity Gains for Various EO-PTC and EO-PTC with VBTC Scenarios

Train Type	MAS (mph)	TC_L (Mile)	EO-PTC* Headway (Mile)	EO-PTC with VBTC Headway† (Mile)	Headway Reduction of EO-PTC with VBTC vs EO-PTC*† (%)
Freight	60	1.2	4.99	4.39	12.0%
Expedited	60	1.2	3.70	3.10	16.2%
Passenger	79	1.2	2.92	2.32	20.6%
Freight	60	2.5	6.29	5.04	19.9%
Expedited	60	2.5	5.00	3.75	25.0%
Passenger	79	2.5	4.22	2.97	29.6%
Freight	60	4.5	8.29	6.04	27.2%
Expedited	60	4.5	7.00	4.75	32.1%
Passenger	79	4.5	6.22	3.97	36.2%
Freight	49	1.2	4.28	3.68	14.0%
Expedited	49	1.2	3.43	2.83	17.5%
Passenger	59	1.2	2.39	1.79	25.2%
Freight	49	2.5	5.58	4.33	22.4%
Expedited	49	2.5	4.73	3.48	26.4%
Passenger	59	2.5	3.69	2.44	33.9%
Freight	49	4.5	7.58	5.33	29.7%
Expedited	49	4.5	6.73	4.48	33.5%
Passenger	59	4.5	5.69	3.44	39.6%

** The headway results for EO-PTC also apply to B-QMB.*

† The headway results for EO-PTC with VBTC also apply in most cases to B-QMB with VBTC.

9. Conclusion

The VBTC concept has the potential to increase traffic efficiency and railroad network capacity by offering reduced train headway. Other potential benefits include non-vital broken rail location determination and increased granularity for controllable signals.

This project focused on two different aspects of the VBTC research: concept development and testing a prototype using a supplier's equipment. The team researched the VBTC basic system architecture and principles and uncovered some key system performance-related characteristics, proposed a basic VBTC architecture, noted potential issues and limitations, discussed the potential implementation of the VBTC concept within current ITC PTC and future QMB methods of operation, and presented some potential enhancements to the basic concept.

To evaluate the potential of the VBTC concept, researchers developed a test bed using Alstom signaling equipment capable of performing VBTC functions. A field test plan was developed and executed to evaluate the concept over a variety of operational scenarios.

Based on the results of the field testing, the team determined that the devices tested at TTC could perform essential VBTC functions. VBTC should therefore provide a means to reduce train headways and increase the network traffic capacity under various common operational scenarios tested. However, additional evaluation under a broader range of conditions, both operational and environmental, is recommended to fully evaluate performance.

Additionally, researchers conducted a capacity analysis based on the VBTC concept. This analysis provided an estimation of the capacity gains that VBTC can offer in an ideal following move scenario. Estimated capacity gains are highest for homogeneous freight trains operating at uniform constant speed where there is no need for meets or passes. In this ideal scenario, the capacity increase is in the range of 23 to 30 percent beyond the capacity available in EO-PTC/B-QMB, depending on MAS and track circuit lengths. Multiple factors affect the results, including track circuit length, train types (along with their corresponding real-time braking distances), MAS, safety buffer distance for VBTC, and VB size. In a rail network scenario, where meets and passes occur, train characteristics and track speeds will vary. Thus, the expected capacity gains would be smaller than when presented in the ideal mathematical model.

Overall, the project team completed the assigned tasks and realized the desired goals of this phase or research. Future work on this topic should focus on further field testing and operation rule changes, and analysis of potential limitations discovered during this phase. Namely, the VBTC devices should be further characterized regarding changing ballast conditions that affect train movement operation. This can be done by deactivating VB mode and adjusting the number of train movements needed to recalibrate the devices to adjust to a given change in environmental conditions.

Abbreviations and Acronyms

Acronym	Definition
AAR	Association of American Railroads
B-QMB	Basic QMB
BOS	Back Office Server
CAD	Computer-aided Dispatch
ConOps	Concept of Operations
CP	Control Point
DC	Direct Current
EOD	End of Train
EO-PTC	Enhanced Overlay PTC
FMB	Full Moving Block
FRA	Federal Railroad Administration
GPS	Global Positioning System
HOT	Head of Train
IJ	Insulated Joint
ITC	Interoperable Train Control
MAS	Maximum Authorized Speed
Min SSS	Minimum Steady State Separation
NENC	Non-Enforcing or Non-Communicating
PTC	Positive Train Control
PTCEA	PTC Exclusive Authority
QMB	Quasi Moving Block
RTT	Railroad Test Track
Rx	Receive
SB	Safety Buffer
TAG	Technical Advisory Group
TTCO	Train Control, Communications, and Operations
TTC	Transportation Technology Center
Tx	Transmit
TxC	Transmit Current
VB	Virtual Block

Acronym	**Definition**
VBTC	Virtual Block Track Circuit
VRTL	Vital Rear-of-Train Location
WSDMM	Wayside System Data Management Module
WIU	Wayside Interface Unit
WSM	Wayside Status Message

Appendix A.
Virtual Block Track Circuit Assessment Concept of Operation

Contents

1. Introduction

With the wide-scale implementation of Positive Train Control (PTC), the railroad industry is now looking for new methods to reduce train headway and improve line-of-road capacity without significant modifications to the PTC architecture. A virtual block track circuit (VBTC) is one of the options in which the industry has shown interest.

This document is part of the VBTC assessment project. It is not based on the performance of a particular product or prototype, but on VBTC as a generic technical concept.

1.1 Purpose

This Concept of Operations (ConOps) document explains the basic principles, operating concepts, potential benefits, and limitations of the VBTC system, information that will be useful to railroads considering deploying VBTC in conjunction with Interoperable Train Control (ITC) PTC or Quasi-Moving Block (QMB) train control.

1.2 Scope

The ConOps scope includes:

- Describe basic system principles, operating concepts, architecture, and models
- Explain potential benefits and limitations
- Present key features that affect VBTC performance and operation
- Propose a basic VBTC message-reporting assignment solution and operation rules
- Address system-level implementation on PTC and QMB
- Identify safety-related and operation efficiency-related limitations
- Suggest potential future developments

1.3 Document Overview

- Section 2 provides a VBTC background, introduction and overview of the current PTC and planned future train control systems.
- Section 3 describes the basic principles of the VBTC system.
- Section 4 describes some system features impacting VBTC system performance and operation.
- Section 5 provides the proposed message architecture under the current WSM communication protocol.
- Section 6 explains the proposed basic management rules for VBTC signal indications in operation.
- Section 7 demonstrates the implementation of VBTC in the PTC environment.
- Section 8 demonstrates the implementation of VBTC in the QMB environment.

- Section 9 identifies some safety-related limitations and some proposed mitigations of those limitations.
- Section 10 presents some potential future developments of the VBTC concept.
- Section 11 is the conclusion and summary of this ConOps document.

2. VBTC Background and Overview

This concept document analyzes the virtual block track circuit concept (VBTC). The railway industry has shown an increasing demand for a reduction in train headway to increase traffic capacity without necessarily modifying the current PTC onboard system. This has led to interest in a track circuit-based virtual block solution with potential implementation as part of the QMB train control system.

This section provides background about basic track circuit technology, PTC, new train control methods that leverage existing PTC architecture, and a brief overview of the VBTC system.

2.1 Conventional Track Circuit Model

The conventional track circuit is a circuit-based wayside system used to detect track occupancy and track integrity within a block defined by the locations of insulated joints (IJs). Track circuits were developed to allow for automatic wayside signals for maintaining safe separation between trains. PTC builds upon this infrastructure to enforce separation between trains. The key components in the most basic conventional track circuit are a track circuit relay, a power source, IJs, and track circuit resistors.

Figure 1 shows a model for a basic conventional track circuit where the power source and the track circuit relay are located at opposite ends of the track circuit block. Based on a fail-safe principle, the track circuit relay is normally energized to detect train occupancy or loss of track integrity (i.e., a rail break). When the track is shunted by an effective shunt (0.06 Ohms or lower) or track integrity is damaged, the track relay is de-energized, indicating the track block is occupied, or the circuit is broken.

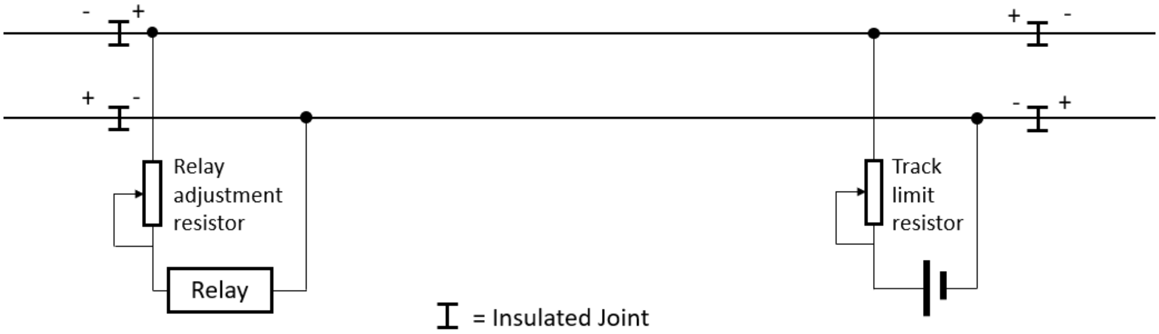


Figure 13. Conventional Track Circuit Model

2.2 DC-Coded Track Circuit

As the technology has evolved, most conventional relay-based track circuits have been replaced by pulsed DC-coded track circuits.

Figure 2 presents a simplified model for a pulsed DC-coded track circuit where the track relay is replaced by transceivers located on both ends of the track. These transceivers work in coordination with each other based on a synchronized time cycle. In each time cycle, one transceiver is the transmit side and sends out pulsed DC codes, and the other transceiver is the receiving side and receives pulsed DC codes. The coded pulses convey more information than a relay-based DC track circuit. Similar to the relay-based track circuit, when the track is shunted or track integrity is lost, the coded signal is not received on the other end, and the system indicates that the track is occupied or the circuit is broken.

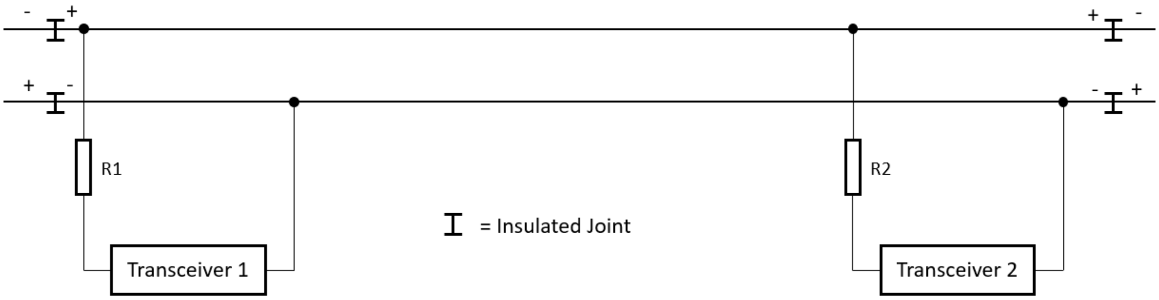


Figure 14. Pulsed DC-Coded Track Circuit Model

2.3 The ITC PTC System

Overlay PTC (O-PTC) is another name for the PTC system that complies with current ITC specifications and is the most widely deployed positive train control system. It uses an onboard locomotive system consisting of an onboard computer, display unit(s), locomotive interfaces, and a data radio. The onboard display provides the crew with a visual representation of the train's current authorities, bulletins, and track profile along with the current allowable track speed and the switch and signal status along the locomotive's current route.

Switch and signal indications are sent over the radio communications network to the locomotive from wayside locations via the PTC wayside interface unit (WIU). Each WIU produces wayside status messages (WSMs) that include the status of all the switches and signals that the wayside device is monitoring. These WSMs are then broadcast so any locomotive approaching the wayside location can listen for the WSMs and update the crew's display based on the data received in the WSM.

The onboard system determines it is approaching a wayside location based on information in the PTC track database. Each wayside location is defined within the PTC track database with location information for the wayside along with the PTC assets that it is monitoring, such as track switches and signals. There is additional information within the track database for each asset including the exact location of that asset, the track on which the asset is located, and the direction of travel with which the asset is associated. The onboard is designed to determine what track the train is on and the direction it is moving, using track data to determine what waysides the train is approaching and what monitored assets are within the train's route. The onboard system then subscribes to or listens for WSMs being broadcast from waysides within its route ahead. The WSMs include status for all assets the wayside is monitoring, but the onboard system uses the track database to determine the assets in the current route, discard those statuses that are not relevant to its route ahead, and update the display based on statuses the onboard system receives.

For O-PTC systems, each signal status the onboard system receives in monitored WSMs is for the signal block that is directly beyond the associated wayside signal location. The monitored WSMs provide no information for the track between locomotive and the signal location.

2.4 New Methods of Train Control that Leverage Existing PTC Architecture

Transportation Technology Center, Inc. (MxV Rail) has developed ConOps and Specifications in conjunction with railroad representatives to support future interoperable train control methods such as QMB, which is intended to be a simple, reliable, and cost-effective modification to existing track circuit-based PTC technology that supports an evolutionary path to Full Moving Block (FMB) train control. QMB is one of three new additional modes of train control that have been identified as an evolution of today's ITC PTC:

1. **Enhanced Overlay PTC (EO-PTC)** consists of realizing operational efficiency by not requiring nor enforcing speed restrictions related to Approach and Advance Approach indications when the onboard PTC is in the "ACTIVE" state. Instead, speed reductions are based on braking distance to targets. This straightforward implementation only requires reconfiguring the track file of the Overlay PTC onboard system and some changes to railroad operational rules.
2. **Quasi-Moving Block (QMB)** governs any train operation in PTC territory by issuing non-overlapping movement authorities, known as PTC Exclusive Authorities (PTCEA). QMB provides more consistency in train control and safety improvements over current Overlay PTC, including the ability to provide collision protection at rear-end and within a joint authority. In addition, QMB is a logical step in migrating to a full moving block train control method. QMB implements full moving block to the extent possible while still relying upon fixed-block track circuits for detecting rail breaks and rollouts. Finally, QMB can provide some moving block capacity benefits in certain implementations.
3. **Full-Moving Block (FMB)** is a concept where the track occupancy is determined by a train's footprint (from front-end to rear-end) instead of track circuits. FMB requires an alternative to fixed-block track circuits for detecting rail breaks and rollouts so that PTCEAs are not tied to fixed block locations. In FMB, the system frequently updates PTCEAs based on each train's moving footprint to achieve near theoretical maximum traffic capacity.

VBTC can be used in conjunction with O-PTC, EO-PTC, and QMB, but not with FMB, since VBTC is a fixed block (i.e., not moving block) system.

2.5 The Virtual Block and Virtual Block Track Circuit Overview

The virtual block concept described in this ConOps document is a method that divides a physical track circuit block (typically delineated by two pairs of IJs) into multiple virtual blocks without adding wayside devices or IJs at each virtual block boundary. Each virtual block created by this method is intended to perform a similar train control support function as a physical track block, with some limitations.

There are multiple solutions to achieve various aspects of virtual block performance. The concept addressed and analyzed in this document is just one approach that is loosely based on a specific type of existing track circuit-based system, referred to as a virtual block track circuit (VBTC) system. Each known virtual block solution has its own set of limitations, which prevents it from achieving the full performance advantages that would be achieved by having shorter physical track circuits of the same length as the virtual blocks.

This proposed concept is based on the use of pulsed DC-coded track circuits, in which the critical function of the VBTC system is to analyze the transmission current sent out from a VBTC transceiver and calculate the distance from that device to the closest shunting item. Through this method, the system can create several location-based virtual boundaries and detect the location of the shunting item (e.g., a moving train). Note that alternative implementations using AC signals, signal reflections, signal propagation times, motion sensors, etc., may achieve the same type of result as pulsed DC signals.

Since VBTC is based on track circuits, it shares some system-level drawbacks of other track circuit-based systems, such as the inability to detect track block status between two shunting items within the same physical block. These issues and others are assessed in this analysis, and application-level suggestions to overcome some of them are provided.

3. The Basic VBTC Physical Theory

This section introduces the basic theory of the VBTC system concept including the basic system model, the relationship between transmission current and track resistance, and the high-level method to identify the location of the closest shunting item.

3.1 Basic System Model for VBTC System

Figure 3 presents a basic VBTC system design depicting a single physical block between two VBTC wayside devices. In this model, the physical block is divided into four equal length virtual blocks (VBs), referred to as VB1, VB2, VB3, and VB4. On each end of the physical block is located a set of VBTC wayside devices (marked as VBTC Device A and VBTC Device B) that both function as transceivers and are coordinated by a synchronized time cycle. R1 and R2 represent the total "wayside" resistance in each VBTC device location.

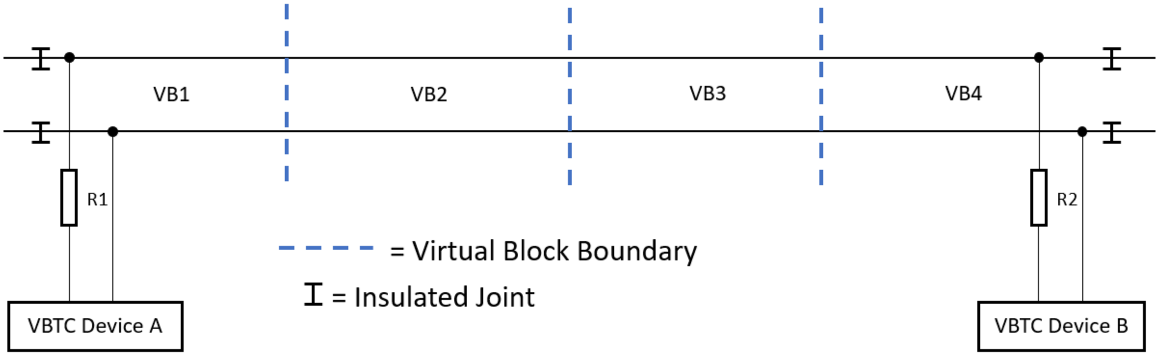


Figure 15. The Basic VBTC System Model

For most of the scenarios in the following sub-sections, a train will enter this physical block from the side closest to VBTC Device A, operating at constant speed and eventually exiting the block from the side closest to VBTC Device B. (Constant speed is used here to simplify the discussion; the speed of train movement can be dynamic in operation.) Both VBTC Devices A and B measure their transmit (Tx) current and receive (Rx) current. While a practical implementation of VBTC may likely use pulsed DC signals in the track to allow alternating transmissions from one end of the block versus the other (and other benefits associated with coded track circuits), to simplify the subsequent explanations, the signal in the track will generally be discussed as if it is continuous DC transmitted from one end of the track only. The output voltage V_{out} from the device can be assumed to remain constant during this discussion.

To better describe the scenario, R_{total} is defined as the total resistance of the track circuit loop, R_{track} is the total resistance of the two rails, $R_{track\text{-}train}$ is the total resistance of rail (only) from the device track bond to the train location (note that this may be different when discussing Head-of-Train (HOT) vs. End-of-Train (EOT)), and R_{train} is the train shunting resistance, ordinarily less than 0.06 Ohms, based on an industry standard.

3.2 VBTC Current Flow Under Normal Train Operation

Based on the system model described above, a train enters the block from the side closest to VBTC Device A, moving at a constant speed as shown in Figure 4, and exiting at the side closest to VBTC Device B. As the train moves, the train position within the block is directly related to the train's location. (Note that the constant speed is to simplify the scenario; in actual operation the speed can be dynamic.) This is the basic principle upon which VBTC works.

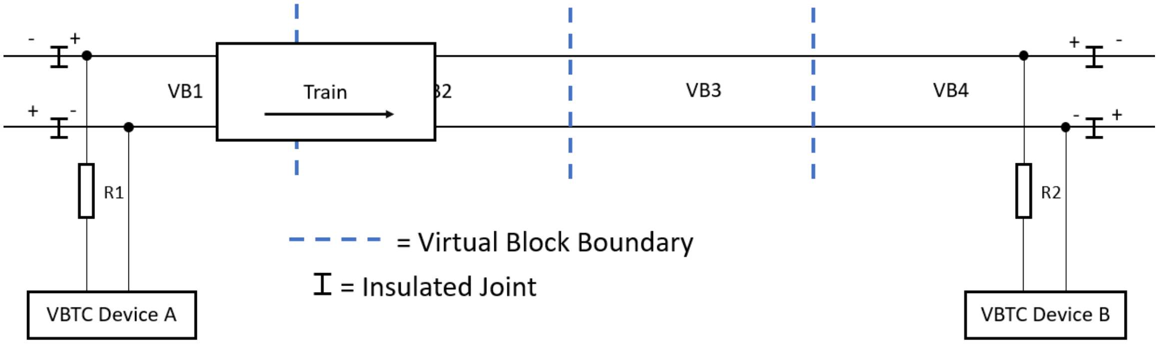


Figure 16. The Basic VBTC System Model with Train Operation

In this scenario, the theoretical Tx current that would be measured at VBTC Device A is shown in Figure 5 as a train passes through the block.

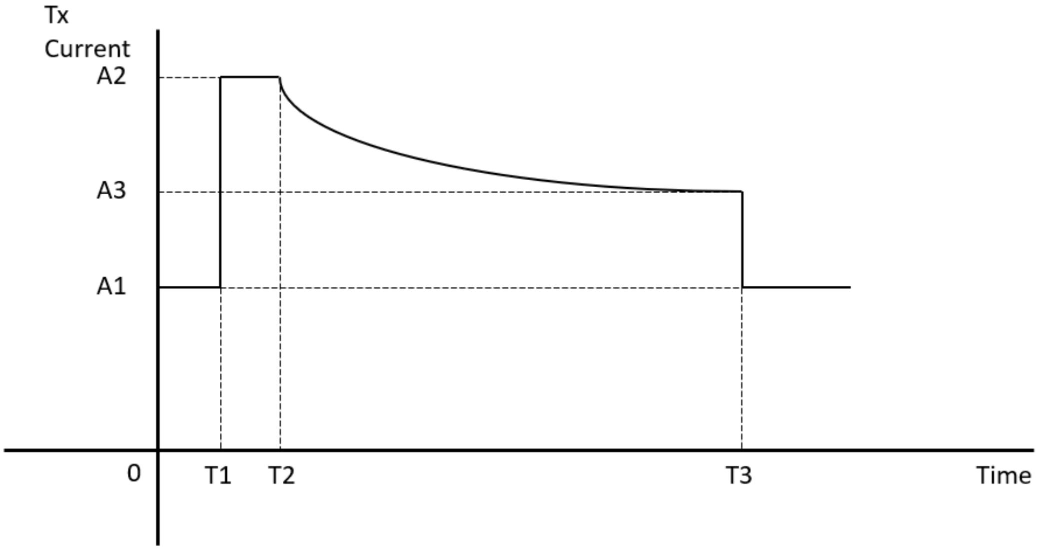


Figure 17. Tx Current Measurement by VBTC Device A during Train Operation Through the Physical Block

The track block is unoccupied between time 0 to T1; the total resistance of the track circuit loop R_{total} approximates the total amount of the resistance through the rail (to the far end and back), R_{track}, plus the wayside device resistances, R1 and R2. R_{total} is expressed as:

$$R_{total} \approx R_{track} + R_1 + R_2$$

Note that the Tx current level of A1 in this period is the lowest that it should ever be during normal operation. This equation is approximate and not exact because the ballast resistance also affects R_{total} but is assumed to be high enough to disregard for the purposes of this explanation.

The time from T1 to T2 represents when the HOT has entered the physical block and the last axle is still within the previous block. During this period, Device A is shunted at the track bond location by axles, so the total resistance R_{total} within the track circuit loop approximates the wayside resistance R1 plus the train shunting resistance R_{train}, expressed as follows:

$$R_{total} \approx R_1 + R_{train}$$

Note that the Tx current A2 in this period is the highest that it should ever be during normal operation.

When the train has entered and is entirely within the physical block, represented as time T2 to T3, the total resistance R_{total} within the track circuit loop is the combination of the wayside device resistance R1, train shunting resistance R_{train}, and the track resistance from the track bond to the train's nearest shunting location (i.e., axle nearest to VB Device A) $R_{track-train}$, expressed as follows:

$$R_{total} \approx R_1 + R_{train} + R_{track-train}$$

Note that as the train moves further through the block, the distance between the track bond at Device A and the train nearest shunting axle increases and $R_{track-train}$ also increases with this distance.

When the train fully exits the physical block, represented as time T3 and beyond, the total resistance R_{total} is restored to the unoccupied state between 0 to T1, expressed as follows:

$$R_{total} \approx R_{track} + R_1 + R_2$$

Figure 6 illustrates the Rx current measured at the VBTC Device A side during this train movement.

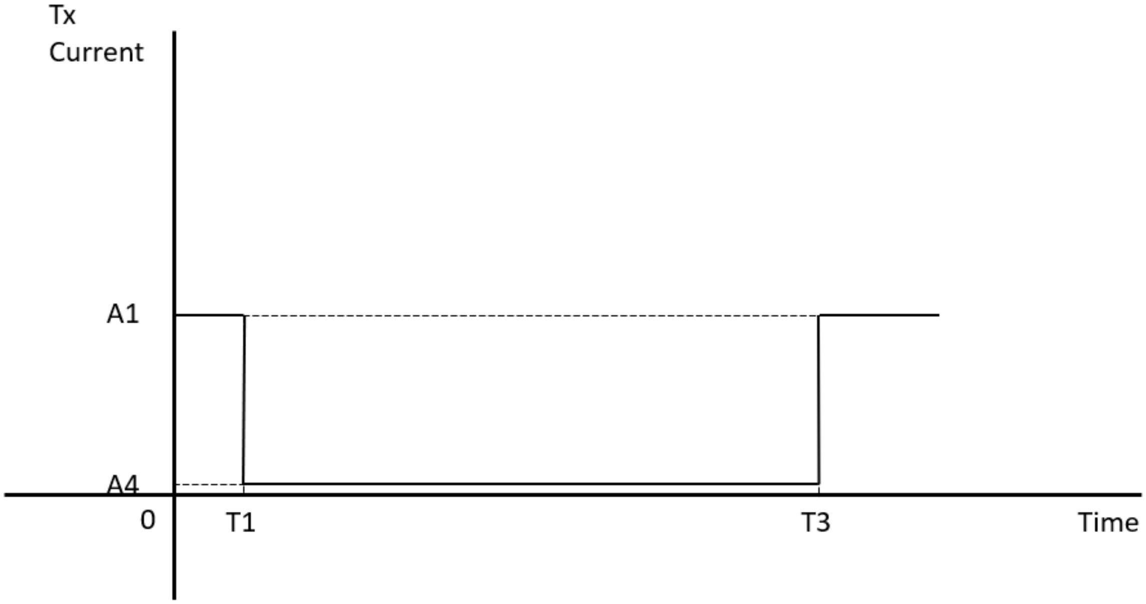


Figure 18. Rx Current Measurement at VBTC Device A During Train Operation Through the Physical Block

In Figure 6, the time points T1 and T3 are the same as time points T1 and T3 in Figure 5, and the Rx current level is equal to A4, which is nearly zero.

During this train operation, the Tx current measured by VBTC Device B mirrors the Tx current measured by VBTC Device A. The difference between each current value point is affected by the difference in wayside resistance R1 and R2 and the fact that the train is moving away from one device and toward the other. Figure 7 shows the current flow measured by VBTC Device B during this movement.

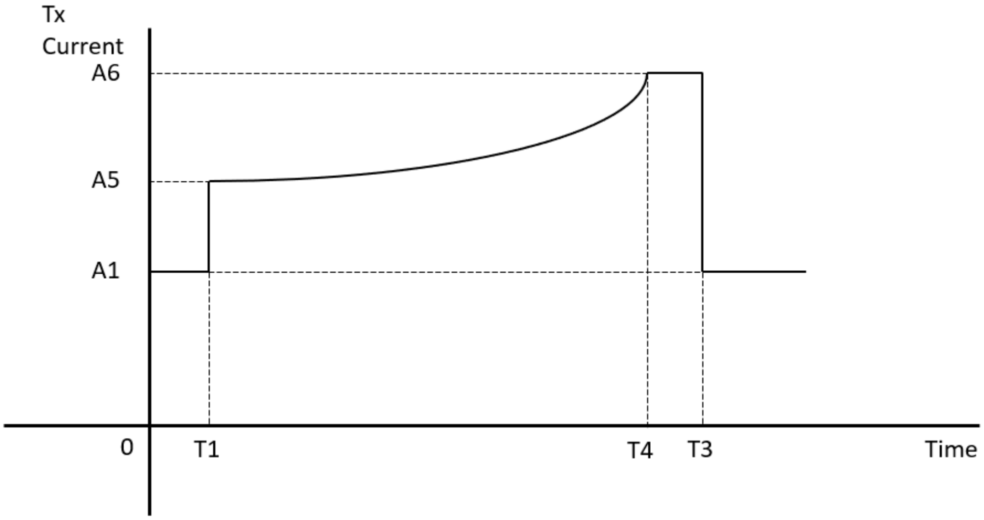


Figure 19. Tx Current Measurement at VBTC Device B During Train Operation Through the Physical Block

The time points T1 and T3 in Figure 7 are the same as in Figure 5; however, the current values A5 and A6 may differ from A2 and A3, depending on the values of R1 and R2. Time point T4 is the moment when the train is overlapping the track bond location of VBTC Device B.

3.3 Relationship Between Train Location and Tx Current

As previously discussed, the main contributing factor to the change in Tx current measured between the time from T2 to T3 by VBTC Device A and the time from T1 to T4 by VBTC Device B is the change in track resistance between the track bond and the closest train axle shunting location (i.e., the location of the rear of the train for VBTC Device A measurements and the front of the train for VBTC Device B measurements) as the train moves. The train shunting resistance R_{train} during train operation and wayside resistance R1 and R2 can be considered fixed values.

As the rail can ideally be considered a homogeneous metal, the resistance of the rail section is directly related to its length. Therefore, for a physical track block, if the wayside resistances R1 and R2 are known (based on pre-measured results or long-term data analysis from the device) and the total length of the physical block, L_{block}, is known (based on the output voltage V_{out} and the measured current at T1 and T3), the real-time track resistance value, R_{track}, can be approximated as follows:

$$R_{track} \approx \frac{V_{Out}}{A_1} - R_1 - R_2$$

Note that a pre-measured value can be used during the initial track circuit set up to simplify the system function instead of calculating a real-time R_{track} value.

Based on the theory introduced above, when a train is currently within the block, the distance between the device track bond toward the closest shunting location can be calculated based on the measured Tx current value.

Figure 8 shows the Tx current measured at the VBTC Device A side as the train operates through the physical block. At time point T5, the distance between VBTC Device A and the closest shunting item (e.g., the rear of the train), identified as D_{train}, can be calculated as follows:

$$D_{train} \approx L_{block} \frac{\frac{V_{out}}{A_D} - R_1 - R_{train}}{R_{track}}$$

Therefore, based on the distance calculation, the nearest shunting location can be determined by the system. The same calculation logic also applies to the VBTC Device B side.

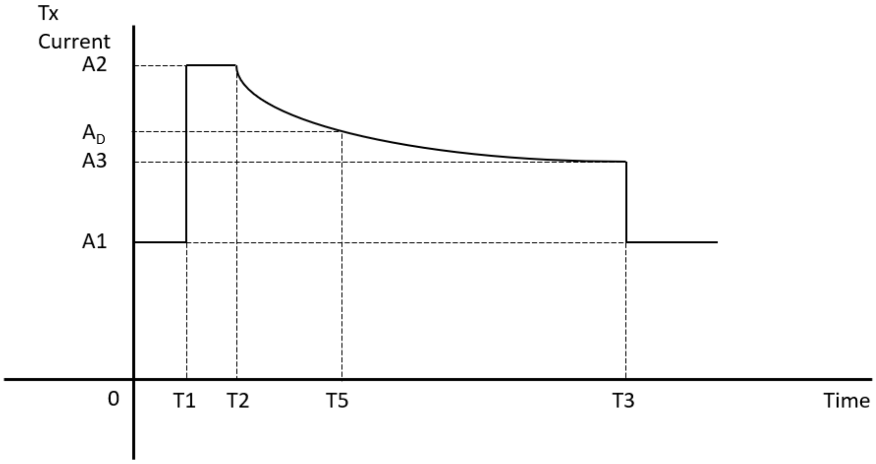


Figure 20. Example of Closest Shunting Location Calculation

3.4 Virtual Block Boundary Calculation and Setup

The VBTC concept is configured to have a pre-defined number of equal length virtual blocks inside a physical track circuit. The locations of their boundaries can be determined by the VBTC system itself based on the total length of the physical block and the same kind of logic used to determine train location in the previous section.

Figure 9 shows expected current versus rear-of-train location as measured by VBTC Device A at location L1 in a VBTC system configured with four virtual blocks per physical block. Each virtual block within the same physical block is to be equal in track length (i.e., L5-L4 = L4-L3 = L3-L2 = L2-L1).

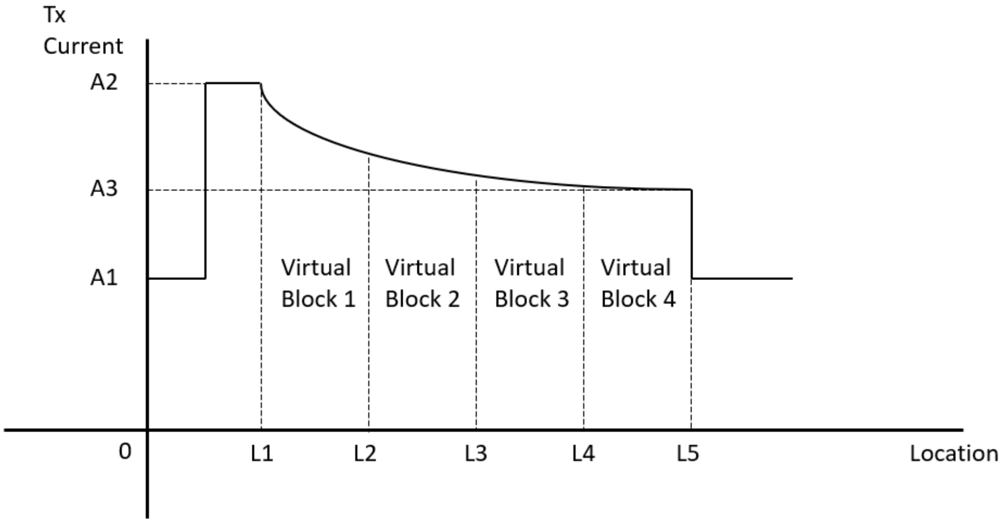


Figure 21. Example of VBTC System Configured with Four Virtual Blocks

Figure 10 shows the calculation of the boundaries of the first virtual block (VB1) within one physical block of a VBTC system. The left most (A-side) boundary L1 is at the location where VB Device A is bonded to the track, and the current value at this location equals A2 while the train is passing over the IJ at L1. VB1's right-most boundary L2 is defined as the train's left-most axle location at the instant that the current at VBTC Device A equals A6. Current values A2 and A3 can be calculated based on the track resistance and other known values. The approximation of current A6 can be calculated as follows:

$$A_6 \approx \frac{V_{out}}{R_1 + 0.25R_{track} + R_{train}}$$

Any shunting item that generates a Tx current between the values of A2 and A6 can be considered as located within the VB1 section.

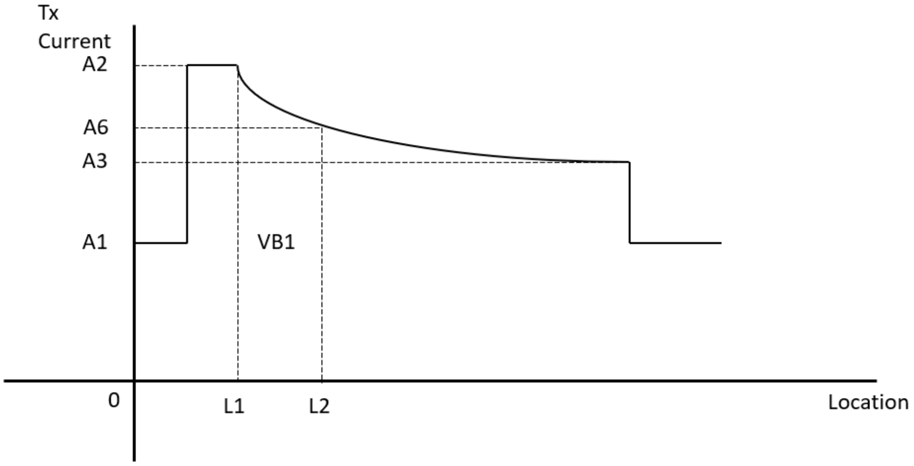


Figure 22. Example of Current Measured at VB Device A as a Train Passes from Left to Right through a Physical Block

If track conditions (especially ballast impedance) are uniform throughout a physical block and there are no non-welded rail joints that cause non-uniform rail impedance, rear-of-train location could be readily determined from currents measured at VBTC devices along with the plots and equations provided in this section. However, because track characteristics are not uniform and not stationary (due changes in weather, flooding, ballast contaminants, etc.), a VBTC system must be calibrated with numerous train movements over the range of potential operating conditions.

3.5 Broken Rail Detection Within an Occupied Block

When a broken rail occurs within a VB and is not overlapped by a shunting item (e.g., a train), the system can identify the existence of the broken rail because the Tx current drops to near zero.

Figure 11 shows an example of a broken rail occurring in an occupied block. Within block T7 is the moment the system detects a broken rail as indicated by the near zero current value of A7 measured by VBTC Device A. Note that the A7 value is different than the Rx current value A4 shown in Figure 11. The shunting location when the broken rail is detected at time T7 can be referred to as the last known shunting location or last known rear-of-train location. This location information may be useful for maintenance purposes but cannot be used for vital train control purposes.

The broken rail scenario is further discussed in Section 9.2.

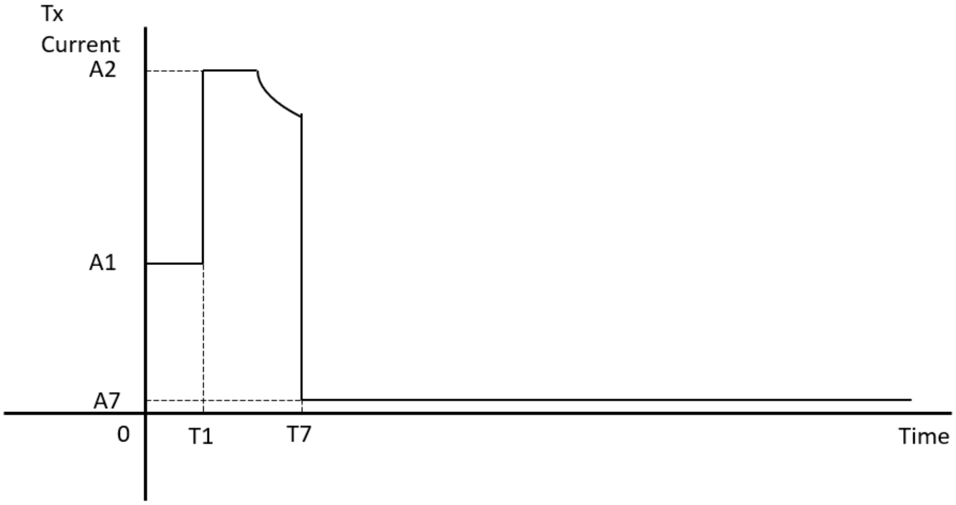


Figure 23. Example of broken rail detection within an occupied block

4. VBTC System Features

The VBTC concept presented in this document is based upon existing track circuit concepts. This VBTC system concept inherited many characteristics from the pulsed DC-coded track circuit and is also affected in similar or more pronounced ways by operating conditions. The following sections introduce some system characteristics that directly impact the system performance and the proposed system architecture.

4.1 VBTC System Detected Occupancy versus Actual Train Occupancy

Being a track circuited-based system, the VBTC concept uses measured Tx current as the primary information for locating a shunting item. This system can only detect and calculate the distance between the VBTC wayside device at one end of a physical track circuit block and the closest shunting item within that block – anything beyond this shunting item is undetectable from this specific VBTC device. The VBTC device at the other end of the physical block has the same limitation, looking into the same physical block from the other direction.

Figure 12 shows a train entirely inside VB3. Due to the current loop limitation, VBTC Device A can only detect that the nearest shunting item (i.e., the train's EOT) is located within VB3 and that VB1 and VB2 are clear. VB4 status is undetectable from the VBTC Device A side. From the other side, VBTC Device B can only detect that a shunting item (i.e., the train's HOT) is located within VB3, and that VB4 is clear. VB1 and VB2 statuses are undetectable from the VBTC Device B side.

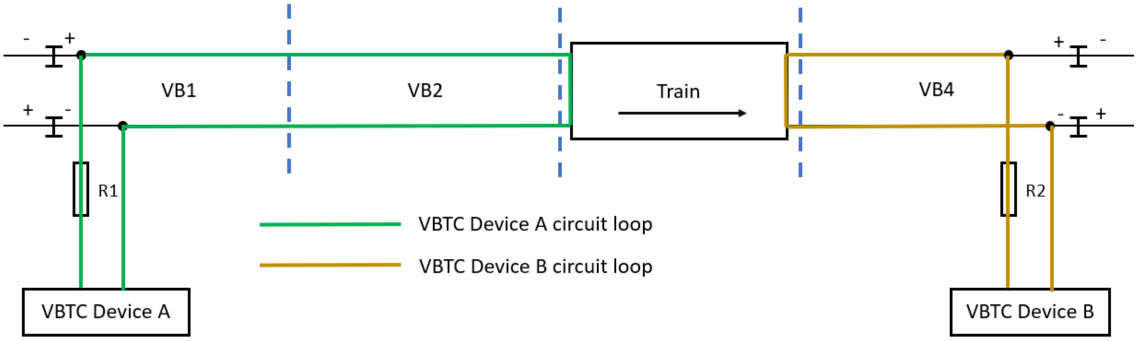


Figure 24. Occupancy Detection Example

Table 1 shows the track occupancy indications from the VBTC devices at each end of the physical block, based on VBTC detection results vs. actual train occupancy in track.

Table 4. Track Occupancy Status Example

	VB1	VB2	VB3	VB4
Actual	Clear	Clear	Occupied	Clear
Device A	Clear	Clear	Occupied	Occupied
Device B	Occupied	Occupied	Occupied	Clear

As shown in Table 1, the detected VBTC track occupancy status can be different from the actual train occupancy. The information from each VBTC device by itself reflects only a partial representation of the actual track occupancy status. Since the devices at opposite ends of the same *occupied* physical block have differing views of track status beyond the nearest occupancy, a VBTC system would typically be configured to have each device only transmit status for those virtual blocks that are not hidden by or beyond an occupancy. This avoids the simultaneous transmission of two, differing WSMs for the same virtual block. Section 5 and Section 6 present how the information gathered by the VBTC devices can be used, based on different system architectures.

During normal operations, the VBTC Device B information is considered more valuable for a train moving unidirectionally from Device A to Device B, as it represents virtual blocks that haven't been traversed by the train.

4.2 VBTC Safety Buffer

The VBTC concept described herein depends on measurement results of the Tx current, which can be affected by changing environmental conditions and system resolution that in turn affect the detection accuracy of the system. Therefore, to ensure the safety of operations and avoid rear-end collisions due to inaccurate detection results, a safety buffer is a necessary protection method.

Figure 13 shows an example of the safety buffer for the VBTC system where a train is entirely inside VB3 and has cleared VB2. However, when adding the safety buffer, VBTC Device A will indicate that VB2 is occupied and will continue to indicate occupied until the train has moved enough that the safety buffer clears VB2.

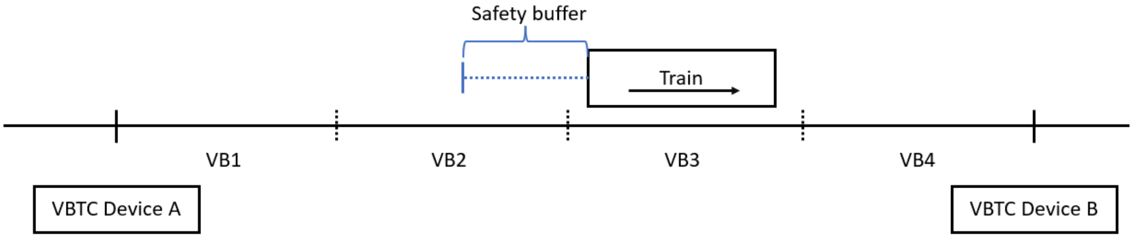


Figure 25. Example of Safety Buffer

Table 2 shows the track status from both VBTC Device A (including the safety buffer) vs. actual train occupancy.

Table 5. Example of Track Occupancy Status Including VBTC's Safety Buffer

	VB1	VB2	VB3	VB4
Actual Track Status	Clear	Clear	Occupied	Clear
VBTC Device A Detection result	Clear	Occupied	Occupied	Clear

Note that for a train operating on track configured with a VBTC system, its front-of-train location data is provided to the PTC system by its onboard GPS, so the safety buffer is only added to the location detected by the VBTC system as being its rear-of-train train location.

4.3 System Track Status Reaction Delay

Pulsed DC-coded track circuits send a pulse through each track block every few seconds in each direction. Due to safety requirements and robustness concerns, these track circuit systems typically change track status indications from more restrictive to less restrictive only after at least two pulse transmission/detection cycles have confirmed the change in status. This repeated confirming pulse cycle method creates a time delay for reporting track clearance, and to a lesser extent, a delay in reporting track occupancy or break (which may or may not wait for a second pulse to confirm the transition). These delays result in a location determination delay that is proportional to the speed at which the train is moving. While this phenomenon is traditionally associated with a physical track circuit block becoming Occupied or Clear, a similar effect plus additional location determination errors (discussed later) occur at virtual block boundaries.

In Figure 14, as a train enters VB3 the VBTC system detects the occupancy. However, only after the pre-defined cycles of repeating verification of VB3 occupancy occur does the system confirm that VB3 is occupied and changes its track status to Occupied while the train has moved further into VB3.

This same delay effect applies to a track status change from Occupied to Clear.

The worst-case distance that the train traversed during this delay can be calculated as follows:

$$\begin{aligned} Distance = {} & Train\ speed * (\ \#\ of\ pulse\ cycles\ to\ react * Time\ for\ each\ cycle) \\ & + Processing\ delays \end{aligned}$$

Note that for detecting occupancy and confirming track clearance, the required time cycles may differ based on system configuration, so the delay distance may also differ between occupancy and clearance detection even at the same train speed. And the delay is also a function of when during the pulse cycle the actual transition to Occupied or Unoccupied actually occurred. When the physical block boundary is also the virtual block boundary, the status change is related to physical block status as well.

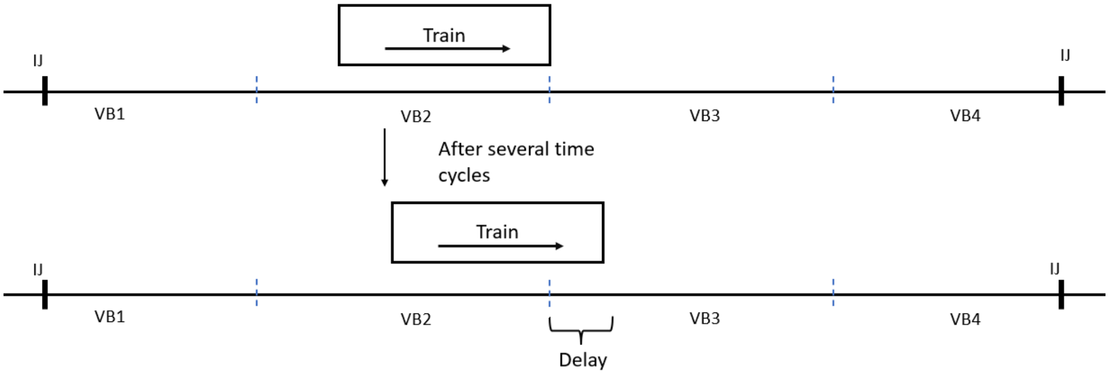


Figure 26. Example of Reaction Delay in the VBTC System

4.4 Entry and Exit Detection Accuracy

The VBTC model previously presented is an ideal model; however, in an actual operational environment, due to system hardware resolution and environmental conditions, the VBTC system will have a distance gap between the exact shunting location and the virtual block boundary for occupancy or clearance to be detected. This gap is referred to as a virtual block's entry and exit accuracy.

Figure 15 illustrates an example of the entry accuracy of VB2 and exit accuracy of VB1 for a train moving from left to right. In an actual operational environment, that accuracy may vary depending on various conditions, even for the same virtual block, and that accuracy will directly impact the system performance.

Notice that for a VB that has an IJ as one of its boundaries, the entry and exit accuracy related to the IJ boundary is considered near zero.

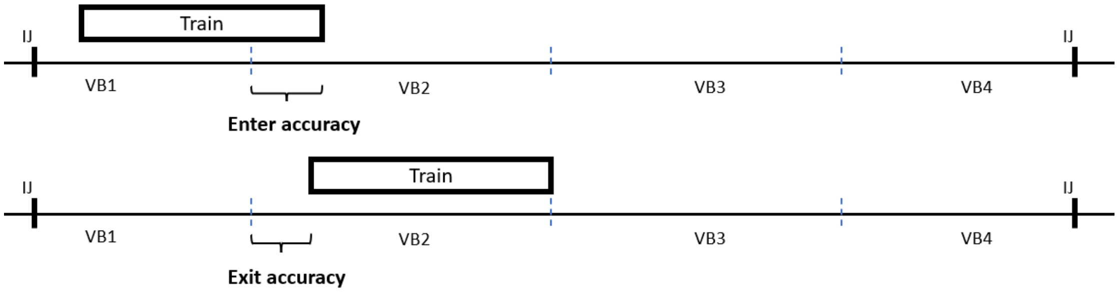


Figure 27. Illustration of VB Entry and Exit Accuracy at the Boundary between VB1 and VB2

4.5 Direction Stick Function

When a train enters a physical track circuit block, a direction stick may be needed for the VBTC device as it needs to understand which current threshold (entry or exit) should be applied to initiate VB-related functions. Therefore, each VBTC device needs to monitor the track circuits on both sides of its associated IJ, regardless of whether it is VBTC territory on both sides.

5. Basic VBTC Data Message and Control Architecture

This section describes how the VBTC system conveys information based on the track status detected by a VBTC device. It also presents a potential VBTC implementation using the current ITC PTC WSM architecture.

5.1 Information Conveyed by a VBTC Device

In an actual operational environment, a VBTC device is installed near each physical block boundary location to gather the track circuit status of both adjacent blocks.

Figure 16 shows a configuration where VBTC Device A is placed at the boundary between Physical Blocks 1 and 2. VBTC Device A detects the VB status of its two adjacent physical blocks, each of which contains four virtual blocks.

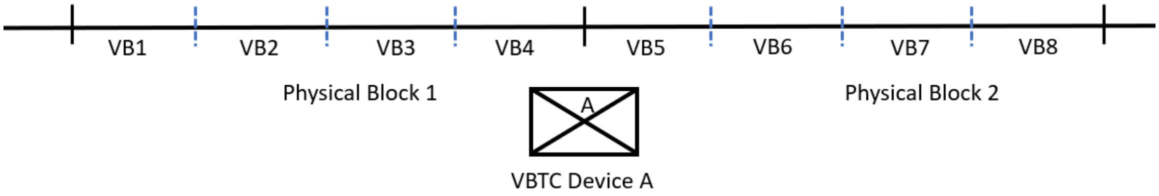


Figure 28. Illustration of VBTC Device and Detected Virtual Blocks from Adjacent Physical Blocks

Table 3 summarizes the virtual block track status from the perspective of VBTC Device A when no occupancy is detected.

Table 6. Virtual Block Track Status for VBTC Device A

Device	VB1	VB2	VB3	VB4	VB5	VB6	VB7	VB8
A	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear

A PTC-equipped train operating with its onboard in ACTIVE state reacts according to the indications of the signals along its path. The status of the virtual blocks can be included as virtual signals in the WSMs from the WIUs that broadcast the status of the physical blocks in the current ITC PTC system. For each virtual block, two virtual signals are added, one at each end, to provide protection for the virtual blocks. Eight virtual signals are added to each physical block in place of the two prior physical signals, based on the example shown in Figure 17. Signals with "L" represent virtual signals that are protecting the train movement from left to right, and signals with "R" represent virtual signals that are protecting the train movement from right to left.

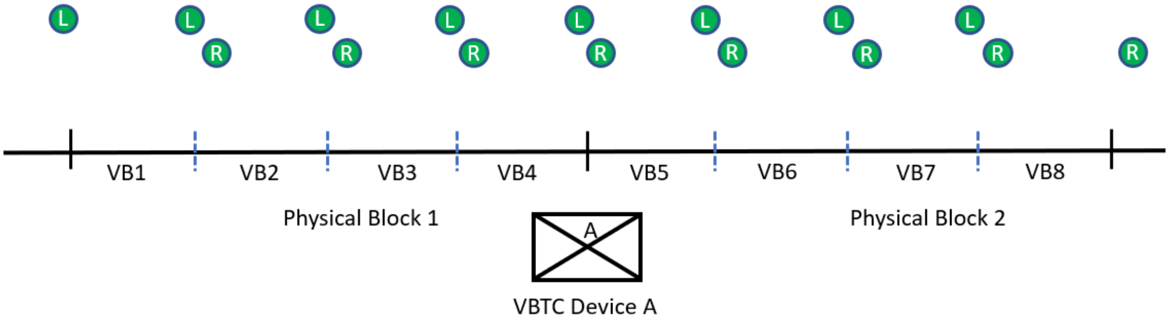


Figure 29. VBTC Virtual Signal Configuration Example for Two Physical Blocks

5.2 Inclusion of VBTC Information in Current ITC PTC WSMs

WSMs broadcasted by the current ITC PTC system can be configured to include the virtual signal device statuses generated by VBTC devices. An ITC PTC onboard does not distinguish between a virtual signal indication versus a physical signal indication in a WSM.

Each WIU will broadcast WSMs containing the assigned virtual signals in the same way as current ITC PTC WSMs.

The theoretical location of every virtual signal is added to the PTC track database so a train can identify each virtual signal ahead in its path, as is done with ITC PTC physical signal locations.

Code (e.g., at the application level) must be included in VBTC devices so that the devices at both ends of the same physical block do not both transmit status for the same virtual signal at the same time.

5.3 VBTC Signal Types and Aspects

Due to the short length of a typical virtual block, a three-aspect or four-aspect signal system is not viable in most cases for train operation on track with VBTC since the train braking distance will often exceed one or two virtual block lengths. Therefore, a VBTC virtual signal is typically configured to indicate only Restricted (Signal Group 2) and Clear (Signal Group 5) aspects. There is a potential exception, however, in cases where VBTC might be deployed in a configuration to permit longer than typical physical blocks, rather than short blocks for reduced headways.

In the VBTC wayside system's basic architecture, each virtual signal is configured the same as a conventional physical signal. An optional advanced version of VBTC configures each virtual signal as an absolute controllable signal or control point (CP) (see Section 10). In this case, each virtual signal is typically configured to indicate only Stop (Signal Group 1) and Clear (Signal Group 5) aspects.

Figure 18 illustrates a train moving from left to right that is currently located within virtual block VB6 with signals for both directions shown. VBTC Device A detects that the closest shunt is located within the VB6 section and considers VB7 and VB8 to be Not Clear (i.e., either occupied or having a rail break) since their states are masked and therefore unknown to Device A. Section 4.1 further describes the associated signal masking issue.

The onboard uses the location of a red signal and track data to set up a Stop or Restricted Speed target as necessary. Details of message management rules are introduced in Section 6.

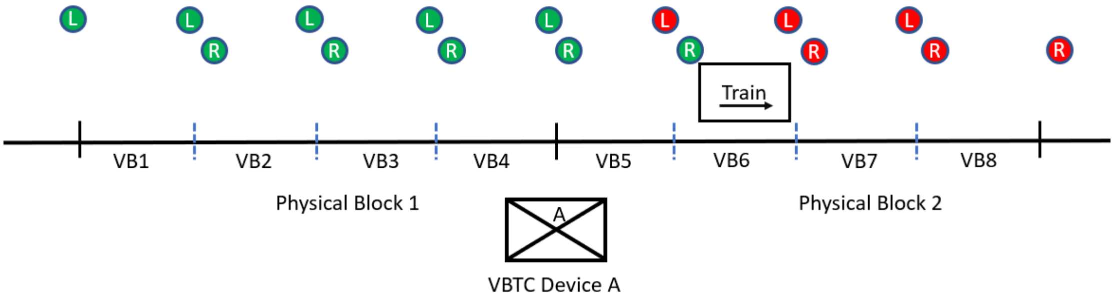


Figure 30. VBTC Virtual Signal Aspect Indication Example

6. Management of VBTC Signal Indications

This section discusses a basic VBTC architecture, called a "single-layer" VBTC system, based on the system principles, characteristics, and the WSM implementation introduced in previous sections. This discussion includes explanations of how the onboard system uses the information delivered by the wayside devices in the same way as the current ITC PTC system and basic rules of system operation. An advanced version of the VBTC system called the double-layer VBTC system is discussed in Section 10.

Figure 19 shows an example VBTC system model with two physical track circuit blocks and three VBTC device sets that was created to help explain the Basic VBTC system architecture. Each physical block contains four equal-length virtual blocks. When no occupancy or rail break is present, each VBTC device determines the (Clear) status of every virtual block within adjacent physical blocks. Since VBTC Device A and Device B both detect the status of all four virtual blocks in Physical Block 1, functionality must be implemented in the VBTC devices to determine which device will report on each of those virtual blocks. This is because the PTC system may not handle simultaneous WSMs from two different sources for the same virtual signal for the same direction of travel in the manner desired. The responsibility for reporting on each VBTC block may be assigned statically or potentially dynamically. It is challenging for VBTC devices to know the status of virtual blocks beyond the detectable range when a shunt exists within the physical block, so a way to relay the status information for those blocks will be a key issue for a dynamic assignment solution.

When a train enters the track in this example, its movement direction will be from VBTC Device A to VBTC Device C. VBTC Device A is located at the entry side and VBTC Device B is at the exit side for Physical Block 1 and VBTC Device B is at the entry side and VBTC Device C is at the exit side for Physical Block 2. The figure shows which of the three VBTC devices senses the status of each virtual block, depicted in terms of signals governing left-to-right train movement.

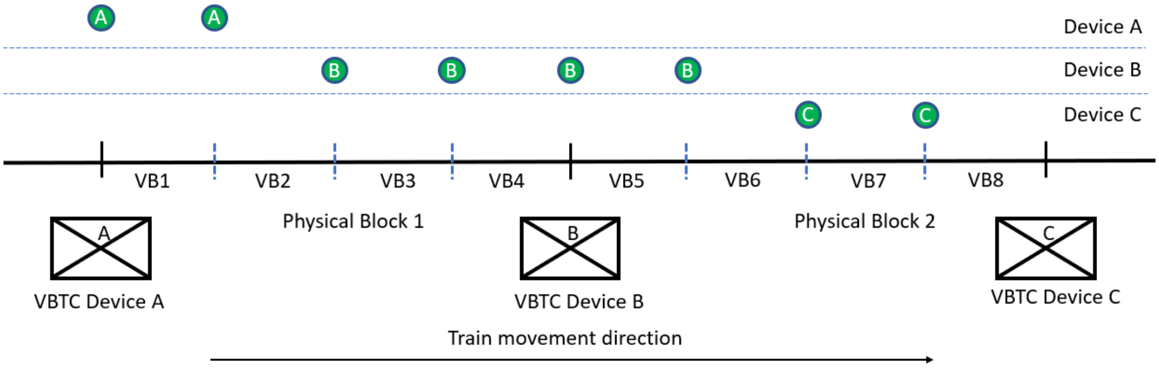


Figure 31. Example VBTC Setup Over Two Physical Blocks to Demonstrate Which Virtual Blocks are Sensed by Which VBTC Devices When No Train is Present

For simplification, only virtual signals within the two illustrated physical blocks and associated with the indicated direction of train movement are shown in Figure 19.

Table 4 represents the virtual block track status as detected by each VBTC device as well as the actual train occupancy track status ("Actual Track Status").

Table 7. Single-layer VBTC System Track Status Table Example

	VB1	VB2	VB3	VB4	VB5	VB6	VB7	VB8
Actual Track Status	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device A Detection Result	Clear	Clear	Clear	Clear	N/A	N/A	N/A	N/A
Device B Detection Result	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device C Detection Result	N/A	N/A	N/A	N/A	Clear	Clear	Clear	Clear
Reporting Device	A	A	B	B	B	B	C	C

The “Actual Track Status” row indicates the true state of each virtual block, either Occupied or Clear. The “Device A Detection Result,” “Device B Detection Result,” and “Device C Detection Result” rows indicate the virtual block status information detected by each of those VBTC devices. The “Reporting Device” row indicates an example of which VBTC device is providing the status of each virtual block.

6.1 Basic Operating Rules for the Single-layer VBTC System

The “single-layer” VBTC architecture is considered the basic VBTC system. This architecture is designed to operate with ITC PTC onboard and office segments “as-is” (i.e., without requiring modification in any way to support VBTC operation). A train’s ITC PTC onboard only uses WSMs from the “incoming” signals (i.e., ahead of it), whether virtual or physical, to identify each block’s status. The onboard monitors the WSMs that indicate the status of virtual blocks that are up to 5-8 miles ahead.

As the current PTC and future QMB onboard systems have a GPS-based location determination system and a track database, the onboard determines which virtual signal locations are ahead (or physical signals when not operating in VBTC territory) and which signal locations have been passed by the front of the train.

Under a basic, single-layer VBTC system, the onboard segment has only one valid information source (i.e., the source of WSMs) assigned at a time for track status of each virtual block. Since each virtual block is monitored by two VBTC devices, those assignments may be configured statically or may possibly change when occupancy and rail break conditions change. In dynamic solutions, these devices must include functionality (e.g., railroad-specific application code) to select which device is assigned to broadcast the WSMs for each virtual block.

For the purposes of the concept developed in this project, assuming four virtual blocks per physical block, the wayside information is assumed to be provided based upon the following example rules for a static reporting assignment solution. However, railroads may implement different algorithms in VBTC device application code, depending upon their specific needs.

- When a physical block is unoccupied, application code in the VBTC devices will transmit the status of the two nearest virtual blocks on either side of the IJ associated with that VBTC device.
- The onboard location determination system is used by the ITC PTC onboard segment to determine the front-of-the-train position relative to each virtual block boundary, and in which direction the train is traveling, since the virtual block boundaries are stored in the track database.

- Based on the front-of-train location, the direction-of-train movement, and the virtual block boundary locations in the track data associated with specific FeatureId (i.e., virtual signals), the onboard segment uses the Device Status Code information in WSMs associated with the virtual blocks ahead and discards the status information about virtual signals behind the front of the train.
- Based on the front-of-train location, the direction-of-train movement, the signal locations in the track data (regardless of whether they are associated with a physical or virtual block boundary), and the train's onboard "horizon" limit (e.g., 5-8 miles), the onboard segment uses WSM information from whichever VBTC device is currently broadcasting the status for each virtual block within its horizon. Track status received from any VBTC devices beyond the onboard segment's horizon is unnecessary and can be discarded by the onboard segment.
- A direction stick is implemented with VBTC devices, as these devices need to understand the direction-of-train movement to apply the related current threshold (i.e., the entry or exit current threshold).
- When an entry-side VBTC device detects a shunt within its assigned virtual blocks that did not originate at the IJ associated with that device, it will report the status of its assigned virtual block(s) up to that shunt leaving the rest of its assigned virtual block(s) as Restricted until the virtual block(s) is (are) detectable.
- If a VBTC device detects that a shunt is moving toward it, no safety buffer will be applied; otherwise, a safety buffer will be applied to protect the location uncertainty region behind the train.
- When a train enters a physical block and passes over the IJ at the block's entrance, the entry-side VBTC device associated with that IJ is shunted so that it can no longer detect the status of any virtual blocks within the newly occupied physical block. When this situation is detected by the application code at that device, it transmits WSMs indicating that the virtual block the train just entered is not clear. The status of the next virtual block ahead of the train is based on its memory of the virtual block status prior to this event.
- When an exit-side VBTC device detects an occupancy within its assigned virtual blocks, it will indicate that the occupied virtual block, as well as a potential, undetectable, virtual block beyond it, are not clear until those virtual blocks are detected to be clear (i.e., the train exits the physical block).
- When an entry-side VBTC device detects that a passing train has now cleared its associated IJ, it will report the virtual block status from the IJ to the shunting location (with a safety buffer) based on its detection results while also reporting the status of the potential, undetectable, virtual block beyond based on its memory. The determination that the train has cleared the IJ can be based upon the fact that the device's transmit current into that block has dropped below a configured entry threshold. The state (i.e., memory) stick for this undetectable virtual block will be removed once the shunting item (e.g., a train with safety buffer) is considered past the boundary between this virtual block and previous virtual block.

- If the first virtual block had been reported as occupied by the entry side VBTC device (e.g., due to the leading train with safety buffer) when a new shunting item (e.g., a following train) enters from entry side IJ, then the entry side VBTC device should remove the memory stick, which will result in all the virtual blocks assigned to the entry side VBTC device reporting as occupied until those blocks can be detected as unoccupied.

Application code must also address less common situations, such as determining which device is to transmit WSMs for each virtual block when a train changes directions within a physical block.

As an alternative to the use of WSMs on each side of the physical block, the WSMs could be provided by the entry or governing side of the track circuit only. This is illustrated in Figure 20. Once a train enters the physical block (e.g., at Device A), it receives the WSMs from the entry side. The WSMs for the virtual blocks from the entry side will still be used by the onboard because even though the train has passed the geographical location of the entry side, it may not yet have passed the geographical locations of the virtual block boundaries.

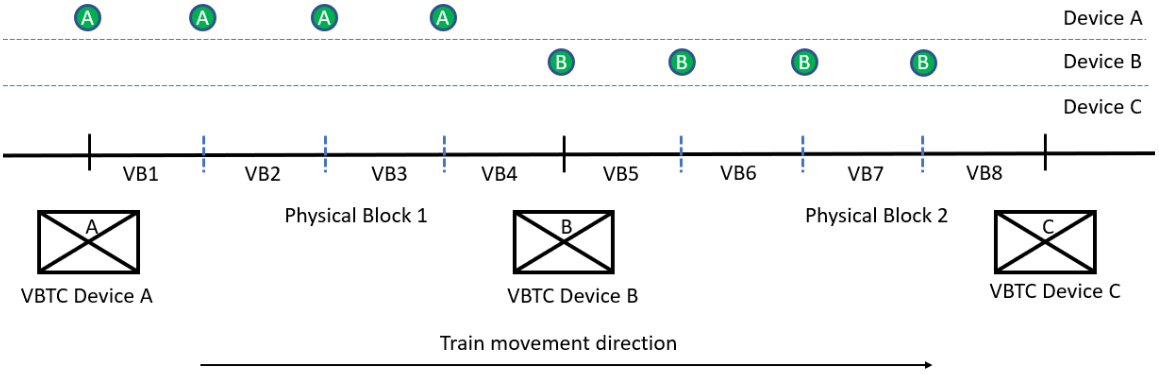


Figure 32. Example VBTC Setup Over Two Physical Blocks to Demonstrate the Alternative Method Where WSMs are Provided by the Entry Side of the Track Circuit Only

Once a train enters the physical block, the entry side can no longer detect any issues in the virtual blocks for that given train. However, it is possible to use "memory stick" logic so the entry side can still relay that the virtual blocks are clear, similar to the operational scenario of two trains in the same physical block. This affects the maximum capacity of the VBTC system. When a following train enters the shared physical block, and then the leading train exits the shared physical block, there is no method to clear the previously occupied virtual blocks. Figure 21 illustrates this potential capacity issue. Capacity benefits are still available because:

- A speed restriction is only added toward the end of the physical block, resulting in reduced capacity benefits.
- The scenario is avoided altogether in cases where there is not a shared occupancy (e.g., higher speeds when trains are separated by more than a physical block), resulting in full capacity benefits.

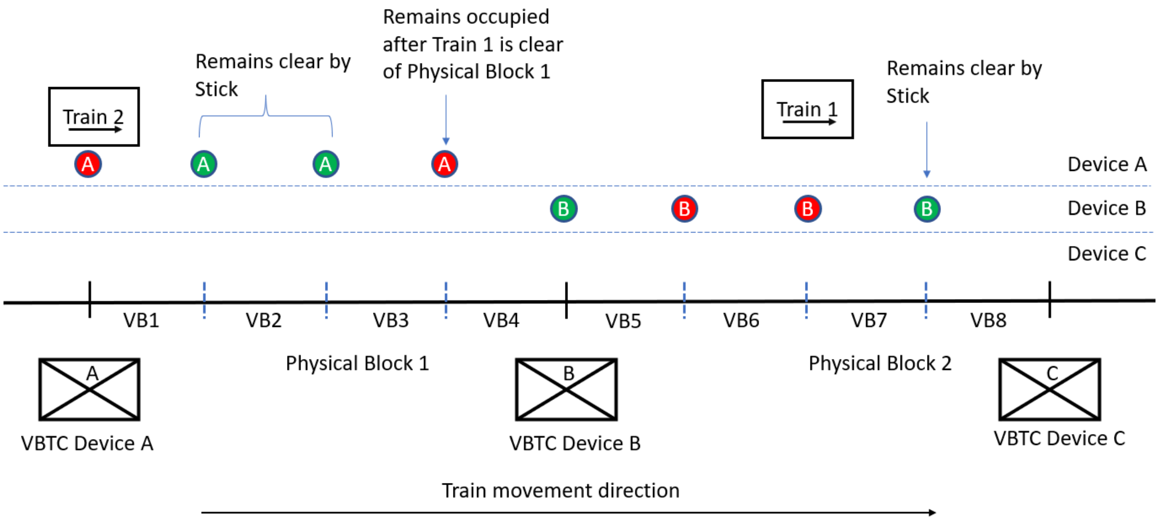


Figure 33. Example VBTC Setup Over Two Physical Blocks to Demonstrate the Alternative Method and the Signal at the VB3/VB4 Boundary Remains Occupied

6.2 Example of Single-Layer VBTC System Operational Scenario

Figure 22 and Figure 23 present an example of a single-layer VBTC system configuration at a time when all blocks are unoccupied. More specifically, the figures show which VBTC device reports the status of which virtual signals, depending upon the direction of train movement the signals are governing. There may be different potential WSM reporting assignments, depending upon how a railroad writes the application code. This is just one possible solution.

Each virtual signal status (Device Status Code) for a particular direction of travel is only broadcast from the assigned WIU at one VBTC device at a time (in the single-layer VBTC system), even though the VBTC devices at both ends of a physical block may be monitoring the same virtual block.

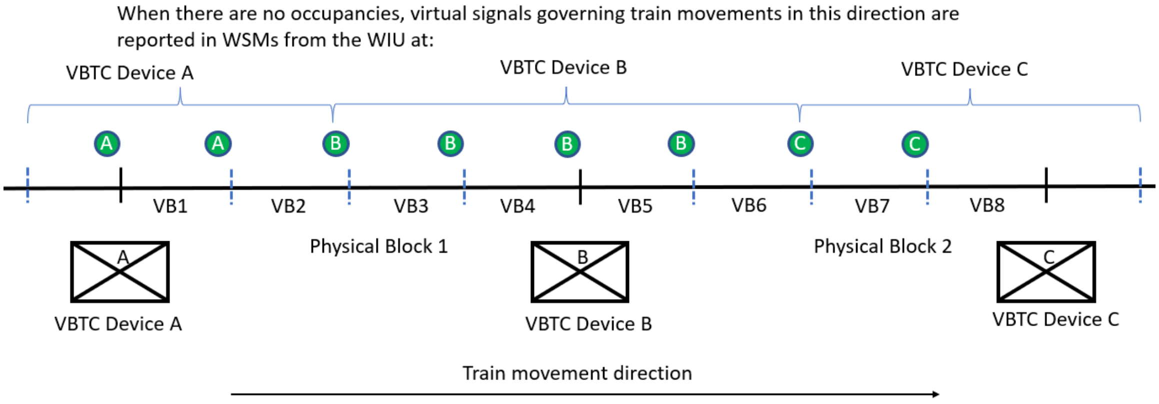


Figure 34. Example of a Potential Single-Layer VBTC System Configuration, Train Movement from Device A to C

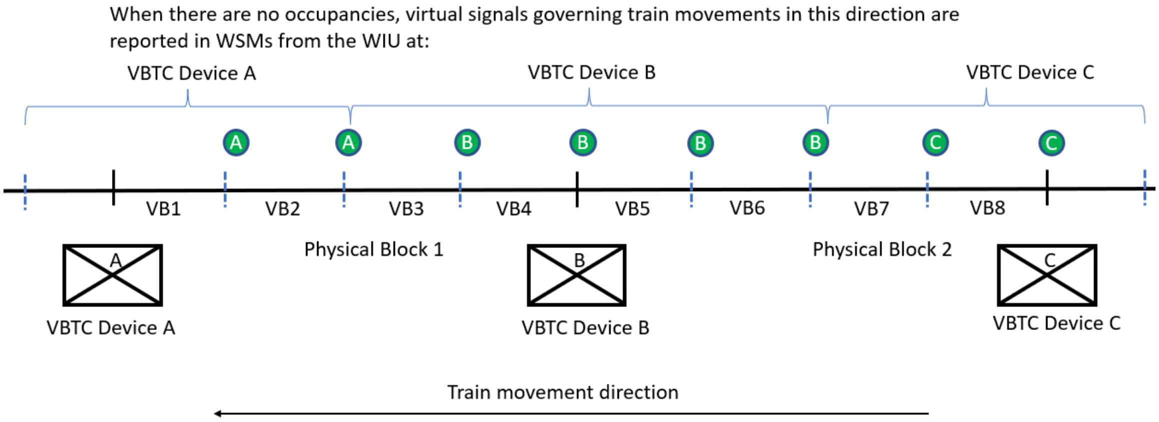


Figure 35. Example of a Potential Single-Layer VBTC System Configuration, Train Movement from Device C to A

Figure 24 shows a scenario where a train with a safety buffer behind (simplified as train) is approaching Physical Block 1. Based on the front-of-train location, direction of train movement, and physical block boundary (i.e., IJ) locations, Block 1 is considered the incoming block. For each virtual block, the onboard receives WSM information from the VBTC device indicated. In this scenario, Device A provides the status for virtual block VB1 and VB2. Status for all virtual blocks further ahead within the train's horizon are provided from the VBTC devices indicated in the figure. However, this is just one possibility for how the VBTC application code might assign WSM reporting responsibilities in this situation. Different railroads might implement different algorithms in their VBTC application code.

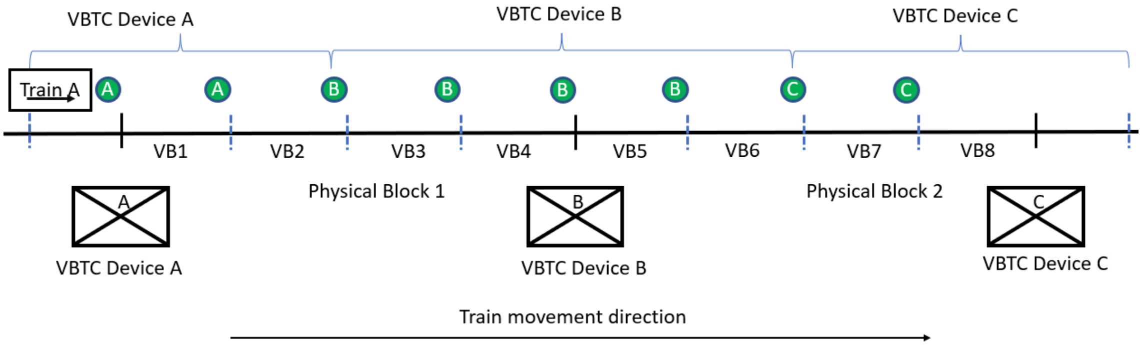


Figure 36. Example of Virtual Signal Status Reporting to an Approaching Train by Different VBTC Device WIUs in a Single-Layer VBTC System

Table 5 shows the virtual block track status determined by each VBTC device as well as the actual train occupancy track status ("Actual Track Status") for the scenario illustrated in Figure 24. The statuses shown in parentheses are detected by the device identified on that line of the table, but they are not transmitted in WSMs from that device to avoid duplicate WSMs for the same virtual block.

Table 8. Example Single-layer VBTC System Track Status Prior to Train Entrance

	VB1	VB2	VB3	VB4	VB5	VB6	VB7	VB8
Actual Track Status	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device A Detection Result	Clear	Clear	Clear	Clear	N/A	N/A	N/A	N/A
Device B Detection Result	Clear	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device C Detection Result	N/A	N/A	N/A	N/A	Clear	Clear	Clear	Clear
Reporting Device	A	A	B	B	B	B	C	C

For this scenario (a train not having yet entered Physical Block 1), the onboard of the approaching train receives status for VB1 to VB2 from VBTC Device A, status for VB3 to VB6 from VBTC Device B, and status for VB7 to VB8 from VBTC Device C.

Figure 25 shows the moment just after the front of a train enters Physical Block 1 and passes WIU A (VB Device A). The memory stick function is applied for VBTC Device A so that VB2 will be shown as Clear, which is the status before the train enters the block.

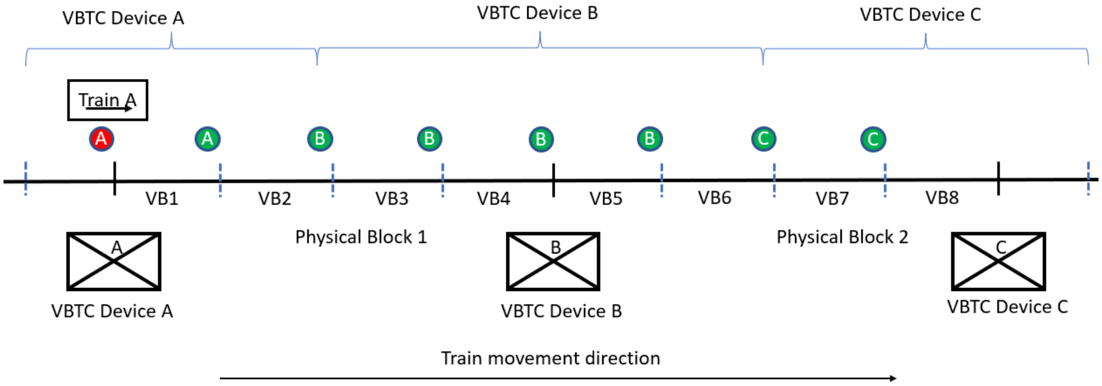


Figure 37. Example of Train Operation with Single-Layer VBTC System, Train Entering Physical Block 1

Table 6 shows the virtual block track status generated at each VBTC device as well as the actual train occupancy track status ("Actual Track Status") for the scenario illustrated in Figure 25.

Table 9. Single-layer VBTC System Track Status as Train Enters VB1

	VB1	VB2	VB3	VB4	VB5	VB6	VB7	VB8
Actual Track Status	Occupied	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device A Detection Result	Occupied	Clear (Stick)	Clear	Clear	N/A	N/A	N/A	N/A
Device B Detection Result	Occupied	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device C Detection Result	N/A	N/A	N/A	N/A	Clear	Clear	Clear	Clear
Reporting Device	A	A	B	B	B	B	C	C
Onboard Action	Ignored	A	B	B	B	B	C	C

Note that the onboard ignores VB1 status as the front of the train has already passed the block boundary of that virtual signal and continues to move to the right side of the diagram.

As the train moves further into the same physical block, it continues to listen to the WSMs from the same devices as well as new ones as they come within its horizon until its front passes the virtual block boundary. The onboard then discontinues using the status from the VB associated with that boundary.

Figure 26 shows a scenario where the train is still within Physical Block 1 but has moved into VB2.

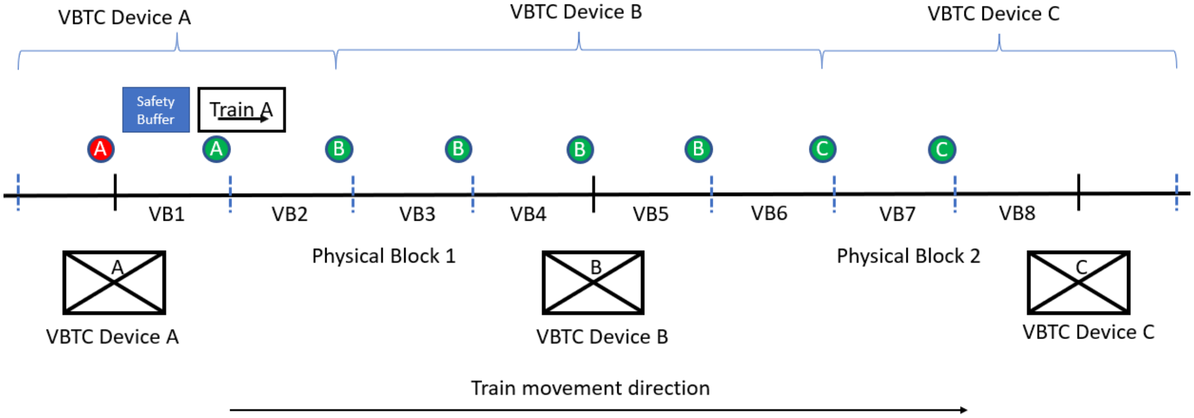


Figure 38. Example of Train Operation with Single-Layer VBTC System, Train Entering VB2

Table 7 shows the virtual block track status generated at each VBTC device as well as the actual train occupancy track status ("Actual Track Status") for the scenario illustrated in Figure 26.

Table 10. Single-layer VBTC System Track Status as Train Enters VB3 and releases VB1

	VB1	VB2	VB3	VB4	VB5	VB6	VB7	VB8
Actual Track Status	Occupied	Clear	Clear	Clear	Clear	Clear	Clear	Clear
Device A Detection Result	Occupied	Clear (Stick)	Clear	Clear	N/A	N/A	N/A	N/A
Device B Detection Result	Occupied	Occupied	Clear	Clear	Clear	Clear	Clear	Clear
Device C Detection Result	N/A	N/A	N/A	N/A	Clear	Clear	Clear	Clear
Reporting Device	A	A	B	B	B	B	C	C
Onboard Action	Ignored	Ignored	B	B	B	B	C	C

VB2 is shown Clear due to the memory stick. VB1 will show Clear after the train exits VB1, and VB2 will show Occupied with VB1 Clear, as then VB2 is detectable for VBTC Device A.

When the train enters VB3, VBTC Device B will show VB3 Occupied and VB4 Clear.

After the front of the train enters Physical Block 2, the onboard repeats the steps above and selects information sources for VB track status as the train moves.

Figure 27 shows the scenario after the train enters Physical Block 2 and passes the physical block boundary (i.e., IJ) at location B. In this scenario, the onboard obtains the track status of the virtual blocks within this physical block from VBTC Device B and C.

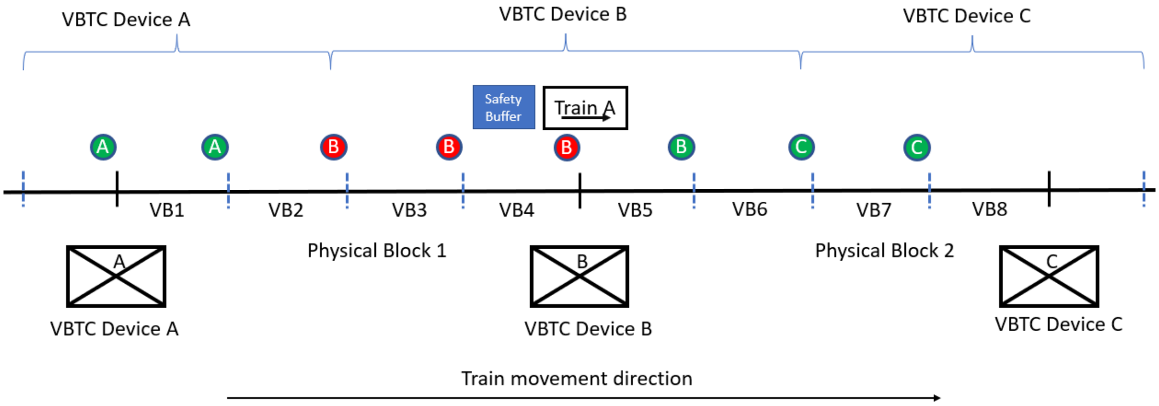


Figure 39. Example of Train Operation with Single-Layer VBTC System, Train Exiting Physical Block 1

Table 8 shows the virtual block track status generated at each VBTC device as well as the actual train occupancy track status ("Actual Track Status") for the scenario illustrated in Figure 27.

Table 11. Single-layer VBTC System Track Status as Train Enters Physical Block 2

	VB1	VB2	VB3	VB4	VB5	VB6	VB7	VB8
Actual Track Status	Clear	Clear	Clear	Occupied	Occupied	Clear	Clear	Clear
Device A Detection Result	Clear	Clear	Clear	Occupied	N/A	N/A	N/A	N/A
Device B Detection Result	Occupied	Occupied	Occupied	Occupied	Occupied	Clear (Stick)	Clear	Clear
Device C Detection Result	N/A	N/A	N/A	N/A	Occupied	Clear	Clear	Clear
Reporting Device	A	A	B	B	B	B	C	C
Onboard Action	Ignored	Ignored	Ignored	Ignored	B	B	C	C

Note that due to the characteristics introduced in Section 4.1, as the train is shunting VBTC Device B location from both sides of the IJ, VBTC Device B will indicate VB3 within block 1 is occupied due to it being undetectable, and VB6 as Clear due to the memory stick function. This also applies to VB1 and VB2, but the status of those two virtual blocks will not be broadcasted by VBTC Device B.

6.3 Operational Scenario with Multiple Occupancies within the Same Physical Block

Like the single train operational scenario presented in the previous section, multiple train scenarios follow the same operation rules. Three different example scenarios are discussed.

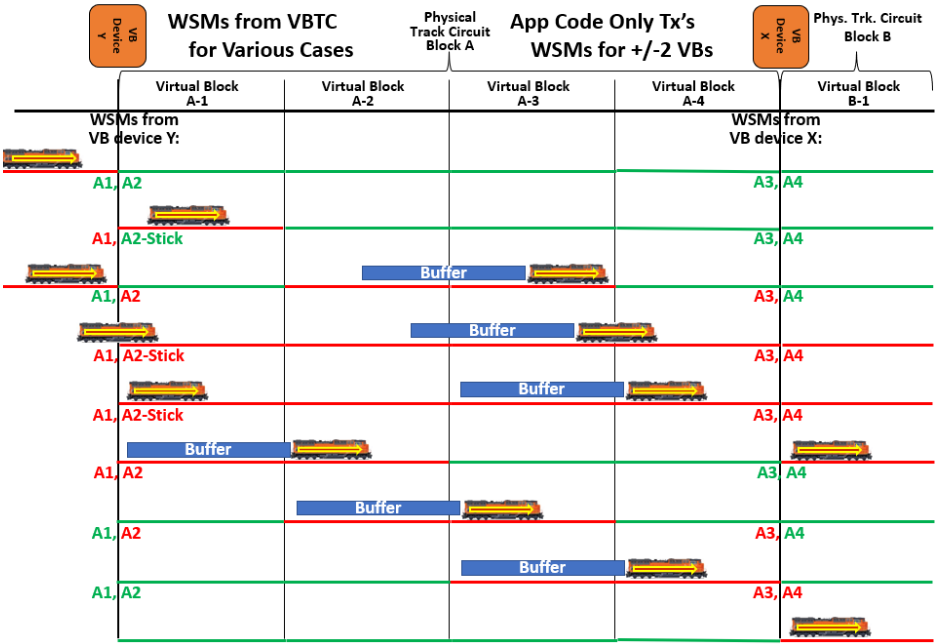
- In Scenario 1, the leading train is occupying the VB2 when the following train enters the physical block.

- In Scenario 2, the leading train is cleared from VB1 and VB2 but still within this physical block when the following train enters the physical block.
- In Scenario 3, the leading train is occupying the VB1 when the following train enters the physical block.

6.3.1 Scenario 1

The entire process when the following train enters the physical block while the leading train (with safety buffer) still occupies the A2 is shown in Figure 28; the status of virtual block A1-A2 is broadcast by VBTC Device X and the status of virtual block A3-A4 is broadcast by VBTC Device Y.

In this scenario, the virtual block A2 will show as Occupied after the following train enters the block due to the memory stick function and will be shown as Clear until the VBTC Device A is able to detect the A2 as Clear.



Notes: VBTC applies 1 VB of safety buffer behind a train in this example.
Each VB device reports only on the 2 nearest VBs in each direction.

Figure 40. Scenario 1: Multiple Trains Within Same Physical Block

6.3.2 Scenario 2

When the following train enters the physical block while the leading train with safety buffer still occupies A2, the status of virtual block A1-A2 is broadcast by VBTC Device X and the status of virtual block A3-A4 is broadcast by VBTC Device Y. Figure 29 illustrates the entire process.

In this scenario, the virtual block A2 will show as Clear after following train enters the A2 due to the memory stick function and will be shown as Occupied until the VBTC Device A is able to detect A2 is occupied.

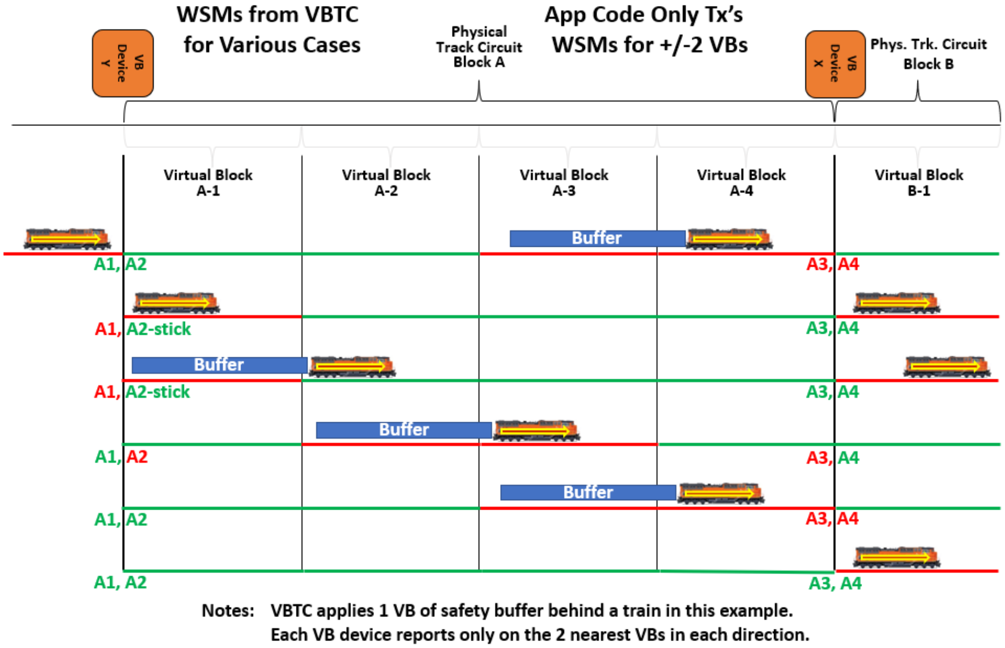


Figure 41. Scenario 2: Multiple Trains Within Same Physical Block

6.3.3 Scenario 3

When the following train enters the physical block while the leading train with safety buffer still occupies A1, the status of virtual block A1-A2 is broadcast by VBTC Device X and the status of virtual block A3-A4 is broadcast by VBTC Device Y. Figure 30 illustrates the entire process.

In this scenario, the virtual block A2 will be reported as occupied and the memory stick should be removed after the following train enters A1 and will be shown as Occupied until the VBTC Device A is able to detect the A2 is occupied. The rest of the process is the same as the other scenarios.

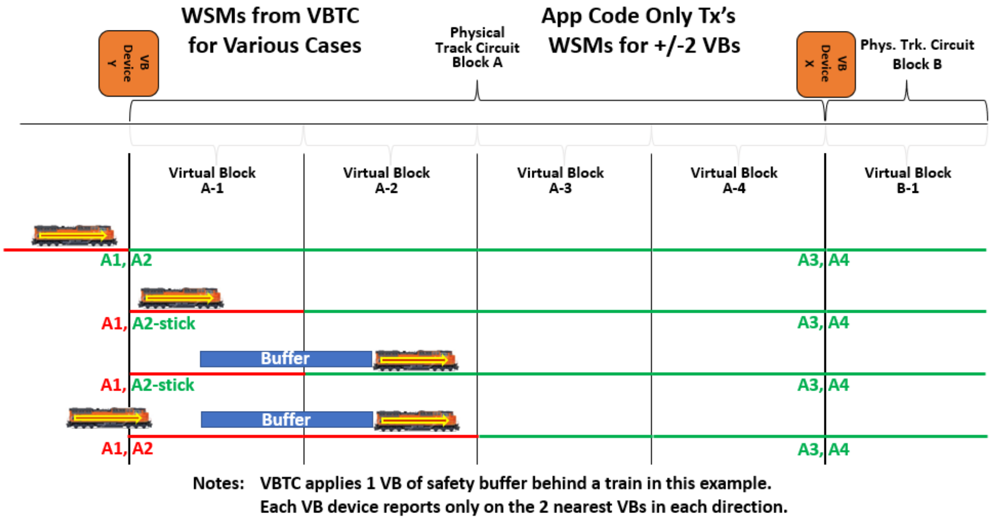


Figure 42. Scenario 3: Multiple Trains Within Same Physical Block

6.4 Advantage of the Single-layer VBTC System

The “single-layer” VBTC system is the fundamental VBTC system and provides all the necessary functions to achieve the key VBTC objectives, i.e., reducing train headways and increasing system capacity without any modifications to the PTC onboard hardware, software, or office. WIUs along the wayside require configuration changes like those that would be made when adding more (physical) track circuits or other physical devices to each WIU’s scope of monitoring responsibility (i.e., to convey the necessary additional WSM information). The extent of modifications or replacements required along the wayside depends upon the type of preexisting track circuits.

7. Operation of VBTC with the Current PTC System

The integration of VBTC with ITC O-PTC requires some configuration updates to the current ITC PTC system but no software (i.e., functionality) changes. These updates include the addition of virtual signal locations and dynamic statuses within the PTC WIU and virtual signal locations in the PTC track database.

7.1 Track Database Updates

Each virtual signal location, track association, and direction association must be included in the track data, just as if it were a physical signal, along with the other items required in the track data model. The position within the WSM where the virtual block status will appear (WiuStatusIndex) for each facing direction also must be defined within the track data for each virtual signal. This will be "0" if each virtual signal is assigned its own WSM. Each virtual signal will convey binary (i.e., two-aspect) status only (e.g., Signal Group 2 or 5 for intermediate/automatic signals and Signal Group 1 or 5 for controlled/absolute signals). No approach or advance approach aspects are conveyed for virtual blocks in most applications of VBTC because the virtual blocks are typically too short for the operating rules associated with those aspects to be valid. An exception is the possible use of approach and advance approach aspects at virtual signals in situations where VBTC is used to allow physical block lengths to be increased rather than to reduce headways. However, that exception is not further addressed here.

7.2 PTC WIU Updates

Where VBTC is deployed, each WIU's configuration is updated to accept the status for each virtual block within its associated physical block and to populate the status of all virtual signals associated with that WIU within its WSMs. VB mode may be active or inactive on a physical block-by-block basis, depending upon real-time conditions determined by the VBTC device about that block and the train(s) passing over it. When VB mode is active, the WSMs produced by the WIU convey individual virtual block signal statuses that may differ from one another within the same physical block. When VB mode is inactive, the WSMs each convey the same status for all four virtual blocks within the same physical block. If there is an occupancy or rail break anywhere in the block, all four of the block's virtual signals will indicate Not Clear, otherwise all four virtual signals will indicate Clear when not in VB mode.

7.3 PTC Onboard System Updates

No changes to the PTC onboard hardware or software are required for basic, single-layer VBTC operation. Only the track data is revised to include four signals (i.e., four for each direction, eight total) for a block that previously had only one signal for each direction. As in ITC PTC operation with conventional track circuits, the onboard system uses the PTC track database to identify each signal (regardless of whether it is physical or virtual), the signal's location, the location within the WSM that signal's information is specified, and other information required by the track data model.

7.4 Transition from Conventional Track Circuit Territory to VBTC Territory

At a boundary between conventional track circuits and VBTC, a railroad may choose to install a control point for each direction of travel. Additionally, the signal aspect and wayside logic should be configured for trains moving out of conventional track circuit territory and into VBTC territory so that the last signal in conventional track circuit territory displays a solid yellow aspect if *any* of the virtual blocks ahead are not clear in the first physical block using VBTC. This is done because conventional track circuit block lengths must be no less than the braking distance of the worst-case train for three-aspect signaling and no less than half the braking distance of the worst-case train for four-aspect signaling, whereas virtual blocks are typically shorter. Figure 31 shows this type of boundary for a train moving from left to right, where the signal at conventional Device A is displaying a yellow (i.e., Approach) aspect due to a virtual block in the physical block reported by VBTC Device B being occupied or containing a rail break.

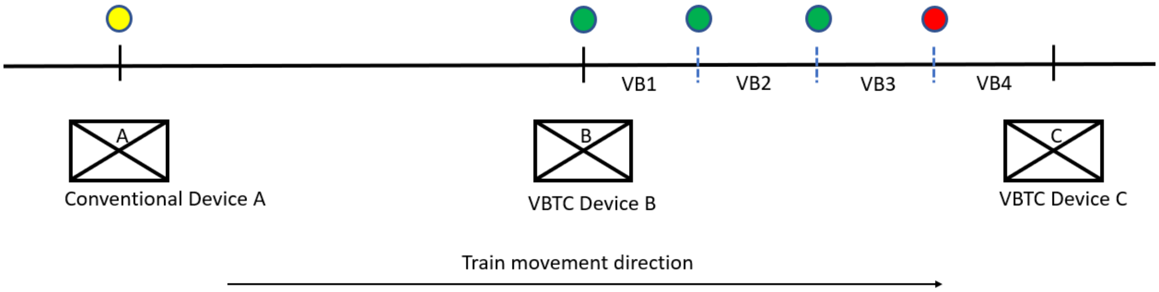


Figure 43. Signal Aspects for a Train Entering VBTC Territory from Conventional Signaled Territory with a VB Occupied

For trains moving in the opposite direction (i.e., moving out of VBTC territory and into conventional track circuit territory), the signal at the boundary (at Device B) for traffic moving in the direction shown in Figure 32 should be a conventional signal (e.g., four-aspect). Operating rules and training must warn train crews that they could experience a red or yellow signal at that first conventional signal location even though the preceding virtual signal indicated Clear.

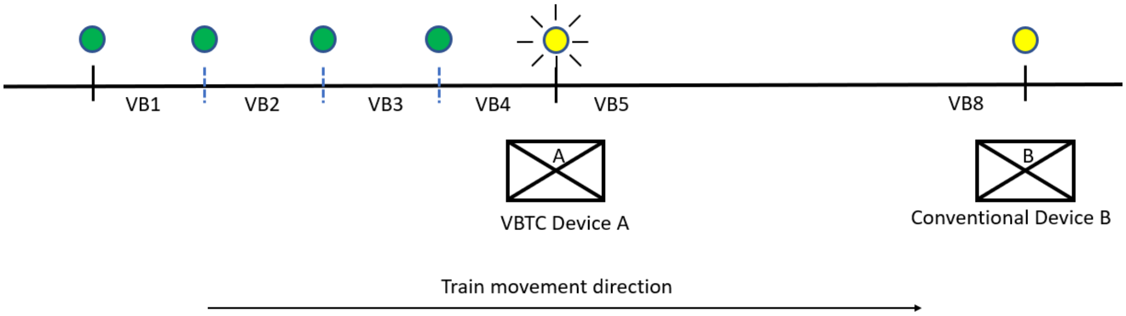


Figure 44. Signal Aspects for a Train Entering VBTC Territory from Conventional 4-aspect Signaled Territory

8. Operation of VBTC with QMB

VBTC may be integrated with QMB train control. In QMB, movement authorities known as PTC Exclusive Authorities (PTCEA) are provided to the onboard segment. The onboard segment follows the more restrictive indication between the PTCEA and the signaling system, whether a conventional signaling or VBTC system. Basic QMB requires track circuits (for detecting rail breaks and unauthorized occupancies) but it functions independently of them, so no additional integration is required with VBTC. The headways and traffic capacity limits under Basic QMB are determined by whatever track circuits are present. Therefore, the headway and traffic capacity benefits of VBTC are directly applicable to Basic QMB.

Note that if a QMB train is not equipped with vital rear-of-train location (VRTL), automatic QMB movement authority roll-ups are based upon estimated rear-of-train location calculated from front-of-train location and assumed train length information. While PTCEAs in Basic QMB provide more protection against a rear-end collision at Restricted Speed than current ITC PTC provides, that additional protection is not fail-safe. Since virtual signals may indicate Restricting (Signal Group 2, not Stop) as their most restrictive state, the same (albeit reduced) risk of rear-end collisions at Restricted Speed exists with VBTC as with conventional signaling. However, further protection can be provided by configuring all virtual signals as absolute signals, having Stop (Signal Group 1) as their more restrictive state. This, however, requires dispatcher involvement whenever two trains need to get closer than one or two blocks apart and could involve configuring each virtual signal to be controllable by the CAD system as a CP. Additionally, the CPs would provide dispatchers with finer resolution control over traffic.

A potential modification to the Basic QMB onboard segment could allow it to use the sub-track circuit granularity provided by VBTC. This benefit would be useful in cases where a QMB train does not have a VRTL system and a Restricted Speed Restriction is required behind it for a following train to operate in the same physical block. Once the QMB train has received input from the VBTC system that a virtual block behind the leading train is Clear, then the QMB train could roll up its PTCEA through that clear virtual block. To do this, a QMB train would need to consider the WSMs for virtual blocks behind it, which would be an enhancement beyond what is included in the current QMB ConOps and specifications.

Another potential modification to Basic QMB would be for the office segment to subscribe to WSMs and use that information for managing movement authorities. This could be helpful in cases where the onboard segment is not communicating with the back office, such as a Non-Enforcing or Non-Communicating (NENC) train. The office segment could roll up the movement authorities of a leading train based on the WSMs that indicate a clear virtual block behind the leading train. However, there are challenges with this concept because the WSM does not identify the train, only the status of the block. Therefore, the QMB concept does not currently consider using WSMs in this manner.

9. Characteristics and Potential Limitations to Consider with VBTC

This section discusses some characteristics and potential limitations related to the VBTC system concept, not particularly focused on specific products or prototypes. Some suggested mitigation measures are also provided. Note that limitations discussed in this section do not necessarily indicate that the VBTC concept poses greater risk than conventional track circuit solutions for safety and stability.

9.1 Multiple Train Protection Within a Single Physical Block

Because VBTC relies on the system's analysis of current applied to track, a VBTC device cannot detect track status beyond the shunting item that is closest to the VBTC device.

When a following train enters a physical block that is already occupied by another train, an undetectable section is created between two shunting items (i.e., trains) that can potentially move the Restricted Target location closer to the following train if a memory stick function is not applied, which typically is between the front of the following train and the end of the leading train.

To better address this issue, an operational scenario is shown in Figure 33.

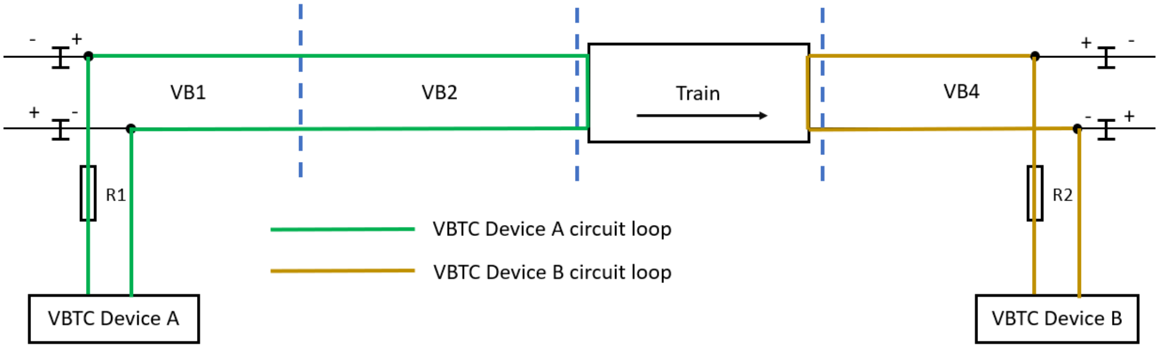


Figure 45. Single Train Operation Scenario Example

In a single-train operation scenario (i.e., no following train), if the whole train consist is within a physical block (Figure 33) the closest shunting items that VBTC devices detect from each end of the track circuit are the front of the train (detected by VBTC Device B) and the rear of the train (detected by VBTC Device A).

Table 9 shows the track status for the blocks in the scenario shown in Figure 33. The table shows the actual status along with the status detected by VBTC Device A and then the status detected by VBTC Device B before VBTC applies the safety buffer.

Table 12. Track Status Table for Single Train Operation

	VB1	VB2	VB3	VB4
Actual Track Status	Clear	Clear	Occupied	Clear
Device A Detection Result	Clear	Clear	Occupied	Occupied (Unknown)
Device B Detection Result	Occupied (Unknown)	Occupied (Unknown)	Occupied	Clear

Under a single-layer VBTC system using the example baseline application function in the scenario shown in Figure 33, if a following train is about to enter the physical block between VBTC Device A and VBTC Device B from the left, the track status on board the following train is determined based on information delivered from Device A for VB1 and VB2 and from Device B for VB3 and VB4. Based on information from Device A and an assumed safety buffer of one block behind a leading train, the onboard will apply a Restricted Speed Restriction (RSR) target throughout block VB2, starting at the boundary between VB1 and VB2.

However, once the following train enters the block as shown in Figure 34, VBTC Device A is totally shunted in both directions by the axles of the following train, so it cannot detect anything other than that it is being shunted. In that situation, VBTC Device A will either transmit Not Clear status for the virtual blocks on which it reports (VB1, VB2, and the two nearest blocks in the previous track circuit) or it will discontinue transmitting any status for some or all those blocks, depending upon the railroad’s application logic. Regardless, this shunt results in an undetectable section between the front of the following train and the rear of the leading train. The same basic situation occurs with O-PTC and conventional track circuits since they cannot detect an occupancy or rail break between two trains in the same physical block either. VBTC does not increase safety risk in this scenario, but unless handled appropriately by application code, it can result in unnecessary operational impact.

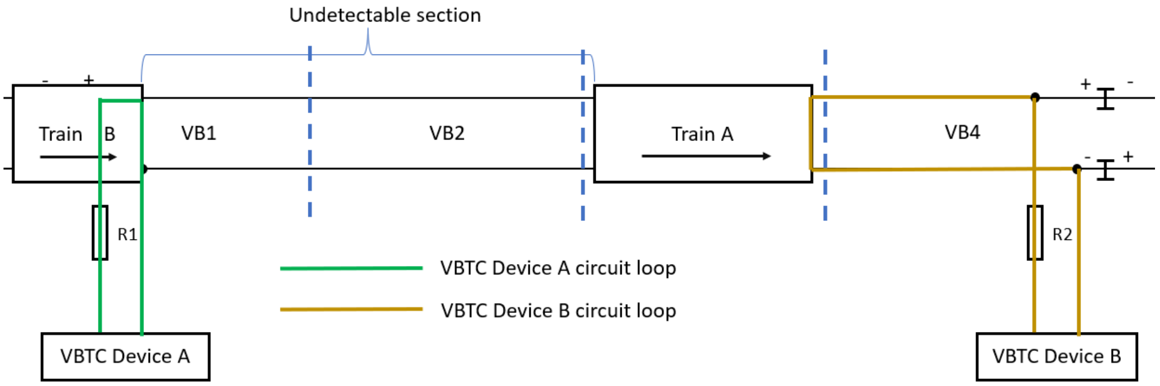


Figure 46. Multiple Trains Within the Same Physical Block Example

When the following train enters the physical block, VBTC Device B continues to report status for virtual blocks VB3 and VB4 without being affected by the following train while the leading train remains in the physical block. If the following train is occupying any of VB1, VBTC Device A only knows that VB1 is not clear and knows nothing about the status of VB2. Table 10 lists the status for VBTC Devices A and B.

Table 13. Track Status Table for Double Train Occupancy

	VB1	VB2	VB3	VB4
Actual Track Status	Occupied	Clear	Occupied	Clear
Device A Detection Result	Occupied	Occupied (Unknown)	Occupied (Unknown)	Occupied (Unknown)
Device B Detection Result	Occupied (Unknown)	Occupied (Unknown)	Occupied	Clear

If no further steps were taken, the Restricted target for the following train would be changed from the boundary between VB2 and VB3 to the boundary between VB1 and VB2, without consideration of the safety buffer and other variants. This change could lead potentially to an operation disruption with the following train encountering a Restricted target unnecessarily where VB2 had been reported Clear prior to that moment.

The preferred mitigation for this issue involves incorporating a "state (i.e., memory) stick" function (e.g., in the VBTC application logic) as described previously. This would cause VBTC Device A to continue reporting Clear status for VB2 temporarily. An alternative solution could involve the double-layer VBTC concept that is proposed in Section 10, if VRTL determination is available. In that case, the system can clear the block based on the location of the end of the leading train.

9.2 Broken Rail Detection and Broken Rail Location Determination

As introduced in Section 3.5, unlike conventional track circuits, VBTC can detect a broken rail within an occupied block if the break is not between two occupancies in the same physical block. While the nearest shunt location is detected and transformed by VBTC into a virtual block occupancy that can be used by the onboard to protect train movements, the system cannot detect the *location* of the broken rail in a fail-safe manner. Also, like conventional track circuits, this system cannot detect the number of broken rails if more than one is within the same track circuit block.

Figure 35 illustrates a scenario where current is detected at an entry-side VBTC device when a train moving at a uniform speed starts to enter a physical block (at time = T1) and then when the train is fully within the block (at time = T8). The rail breaks under the train at a location within VB2. At time T9, the train clears the break location, and the broken rail is detected as the Tx current drops to near zero. Based on VBTC detection, the rear of the train is currently located in VB2, and the detected rear-of-train location is referred to as the last known train location. After that, the train location is undetectable for the VBTC device on that side. Note that while the figure displays current as if continuously present, in an actual implementation, it would generally be pulsed.

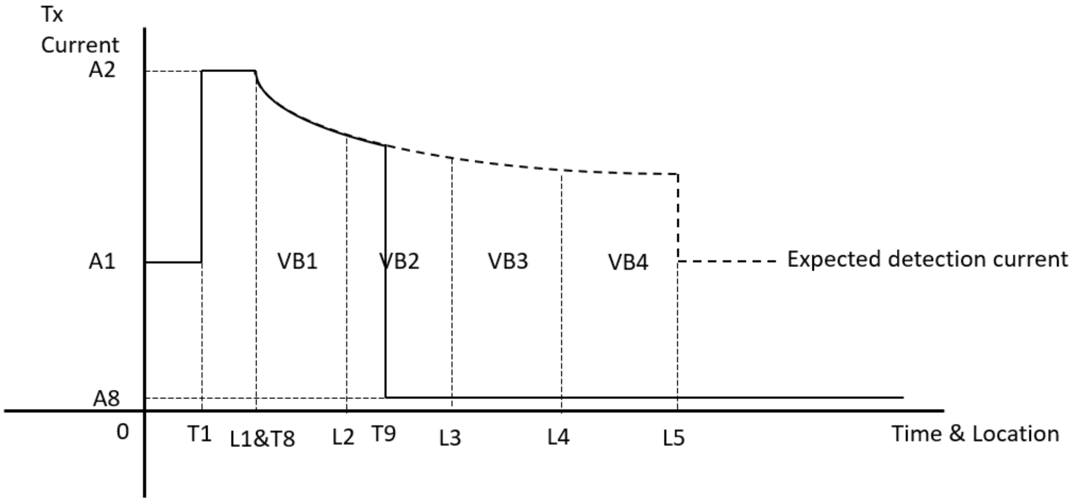


Figure 47. Current Detected at an Entry-side VBTC Device with a Broken Rail Detection at Time = T9

As most rail breaks occur under a moving train, the broken rail location will typically be located in the VB of the last known rear-of-train location, plus or minus the location determination uncertainty of VBTC. However, in the rare event of a spontaneous rail break occurring *after* the train has passed and cleared its location but before the train leaves the physical block (i.e., within the red line area shown in Figure 36), VBTC will provide the same detection result. Thus, the last known train location information cannot be used as a vital indication of rail break location; however, it can be used as non-vital information in support of office and maintenance staff operations.

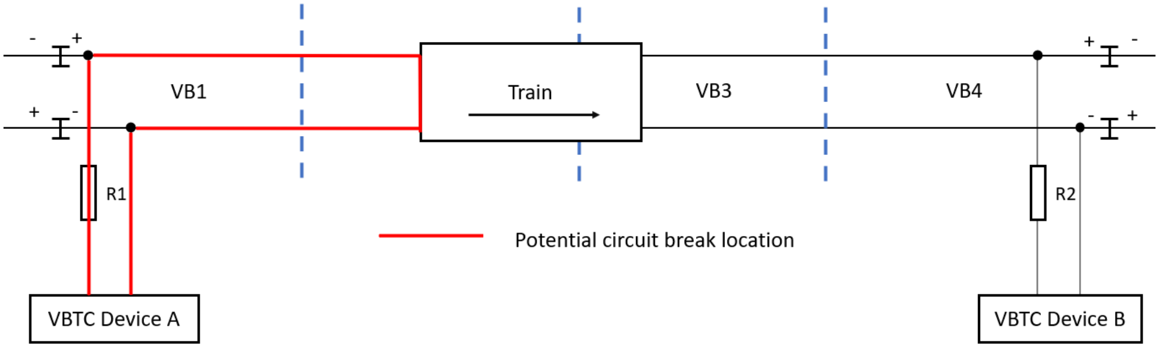


Figure 48. Potential Broken Rail Location

Another reason the last known train location cannot be used as *vital* broken rail location information is the rare possibility of multiple concurrent rail breaks within the same physical block, as illustrated in Figure 37. Once the initial break is detected, it masks the second break.

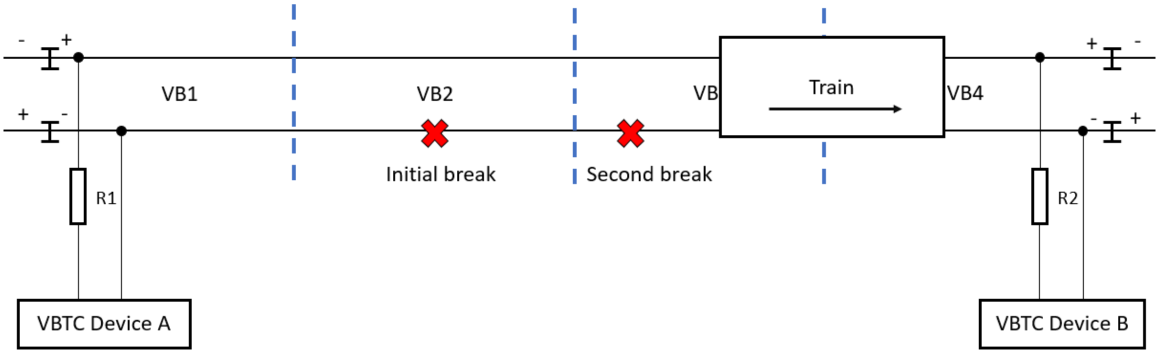


Figure 49. Multiple Rail Breaks

9.3 System Exiting VB Mode and Operating at a Physical Block Level

Since the VBTC function can be based on pulsed DC-coded track circuits, the system can provide conventional physical block-level operation as a fallback option in certain situations when the system self-determines that VBTC functionality cannot be provided (e.g., during loss of calibration or when encountering unsuitable train characteristics). Also, certain hazard events prevent a physical block from operating properly in VB mode (e.g., when a broken rail is detected/present). Although the virtual block headway gain is not available in that track circuit while this situation persists, train operations will already be disrupted due to the rail break, so the temporary loss of VBTC functionality within that block is inconsequential.

Figure 38 shows a leading train (Train A) occupying the VB4 section of a physical block and the allowed speed profile for a following train (Train B) approaching the block with a RSR throughout VB4 due to occupancy by Train A.

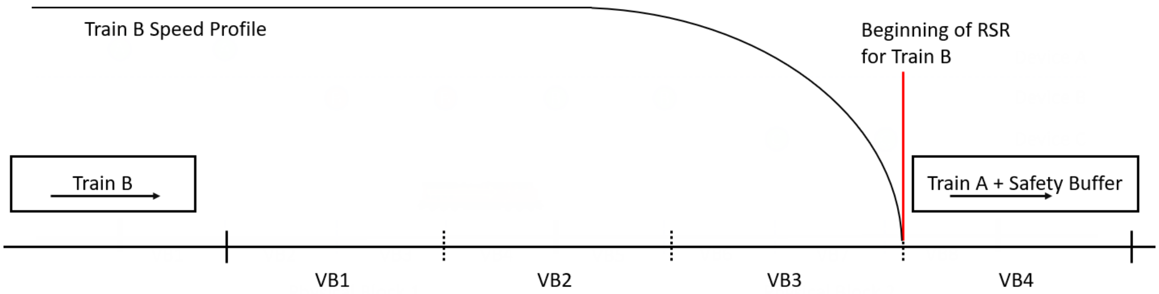


Figure 50. Scenario Just Prior to a Block Exiting VB Mode

If, under this scenario, the VBTC system exits VB mode, it will revert to operating in physical block mode. When that happens, the RSR target for Train B will be changed as the WSMs for all virtual blocks within that physical block will indicate Not Clear. Now, the first red signal encountered by Train B is located at the left physical block boundary, much closer to Train B (see Figure 39). In fact, Train B's onboard indicates that the train is in violation of its authority.

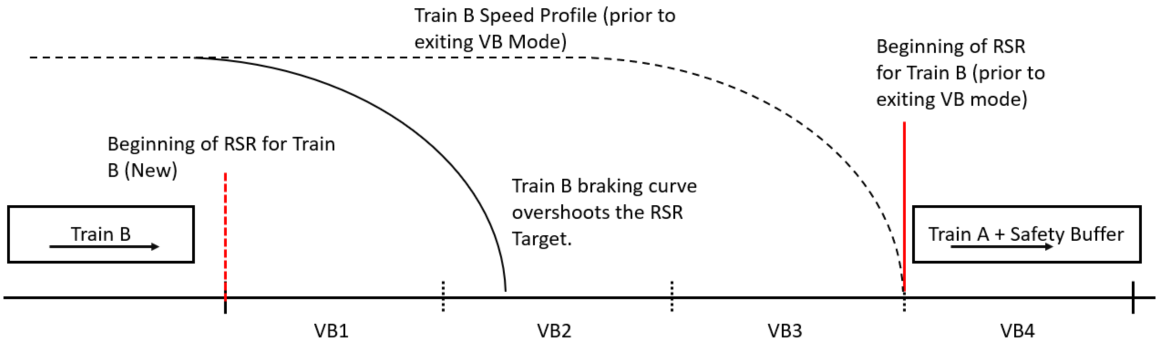


Figure 51. Scenario After System Exited VB Mode

Due to the VB status change from Clear to Not Clear, Train B may not be able to comply with the new RSR target and a reactive enforcement violation may occur. Since there are certain normal and presumably infrequent operating situations in which a VBTC device will drop out of VB mode, some mitigation can be proposed:

- Based on what triggers the system to exit VB mode, if the safety analysis determines that staying in the VB mode for a specified extra period will not directly lead to an operational hazard, a vital timer can be set at the application level similar to the vital timer that is used to protect the switch alignment in current operation.
- A modification to railroad operating practices/procedures may be required so that an enforcement of this type will not be considered as a violation by an employee.

9.4 Risk Associated with Train Pull Apart

Since the virtual blocks in the VBTC system are typically shorter than conventional track circuit blocks, the scenario for pull-apart collision is different in some cases.

After being detached from the main consist of the train, there are three possible movements pull-apart cars can perform: the cars can move forward from the separation location; the cars can remain at the separation location; the cars can move backward from the separation location.

For cases where the car moves forward or remains at the same location, the collision scenarios remain the same as in a conventional track circuit.

For the scenario demonstrated in Figure 40 where a train is pulled apart and the pull-apart car is traveling backward after detachment, there is a potential difference if the following train is unable to stop when VBTC detects the new occupancy against the current direction of train movement or the following train has already entered VB2.

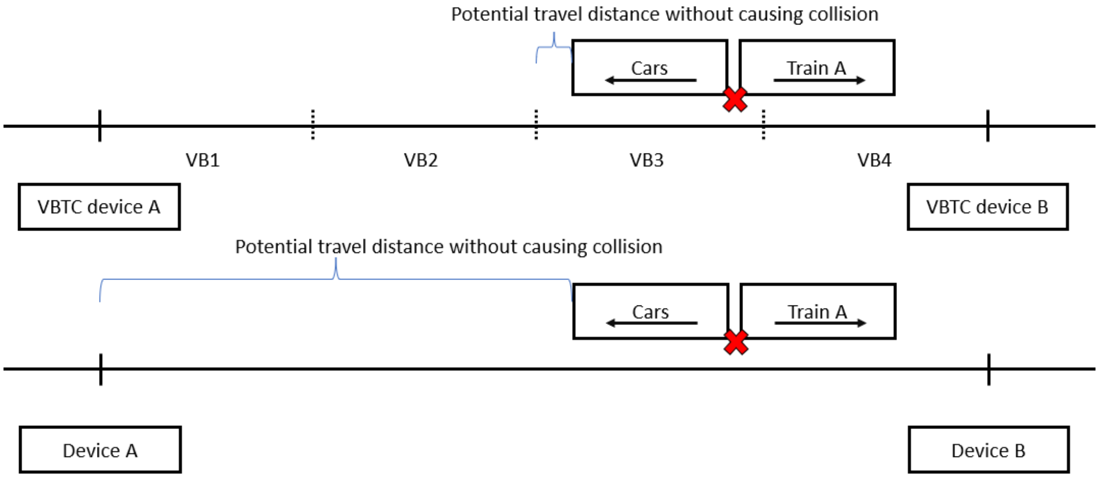


Figure 52. Pull-apart Scenario Comparison

A potential improvement for this issue (along with the same issue where conventional track circuits are in use) is to apply an EOT location determination system, e.g., a VRTL system.

9.5 Risk of Rear-end Collision due to Loss of Shunt

In a railroad operating environment, rusty track surface, or other track or train condition, issues may prevent a train from effectively shunting the track to trigger track circuit detection. In those scenarios, whether the track circuits are conventional or VBTC, a potential rear-end collision can happen since the following train lacks the knowledge of an existing rail vehicle within the block.

For the VBTC system, this issue is different in some scenarios compared to conventional physical block situations.

As Figure 41 shows, a rusty surface zone exists within VB1 and VB2; the train will not create an effective shunt that the VBTC system can detect. However, in this example, a train is within this physical block, and its rear location is over this rusty surface area.

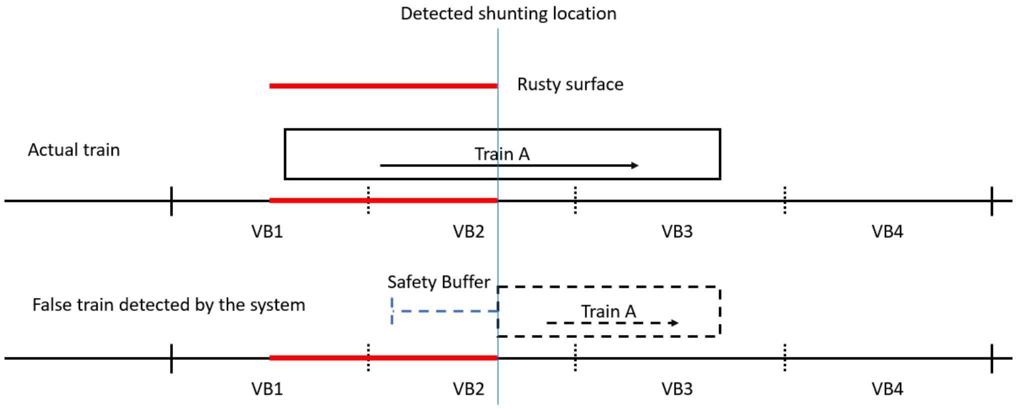


Figure 53. Loss of Shunt Scenario

Since the shunting item (i.e., train) cannot be detected within the rusty surface zone, the shunting location detected by the system will end at the rusty zone. Unless specific mitigation is included in the design, the VBTC system will use this location as the location of the end of this train. As a result of this detection error, VBTC could perceive the train to be shorter than it is, i.e., the detected location for the front of this train will be correct, but the detected rear-of-train location could be the end of the rusty zone.

If the rusty zone within VB2 is long enough to cover the erroneous train safety buffer length, the rusty zone within VB1 is long enough to cover the remaining part from an actual train that is still within the VB1 and a false Clear of VB1 could be created. This could potentially lead to a rear-end collision, as the following train's RSR target would begin at the boundary between VB1 and VB2.

In this scenario with a conventional physical block track circuit, since an active shunt has been detected within the block, the RSR target for the following train is at the physical block boundary so that rear-end collision can be avoided.

A VBTC product may have a function built-in for mitigating the risk associated with loss of shunt. For example, if the Tx current has indicated a significant detection gap during routine train operations, the system will exit the VB mode and fall back to physical block level operation (see Figure 42**)**.

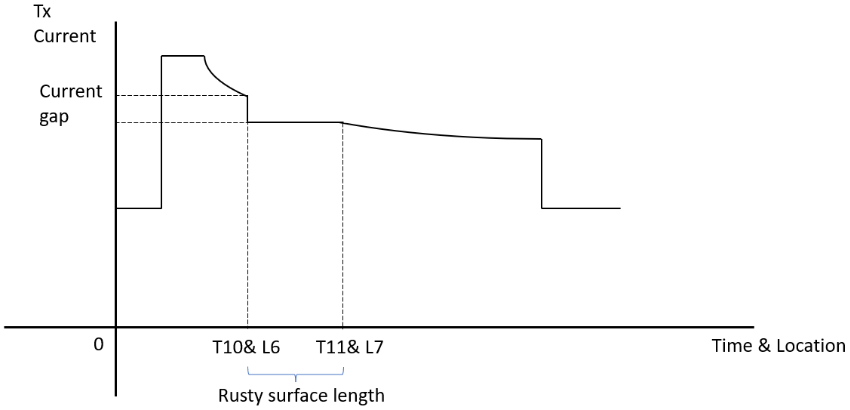


Figure 54. Detected Tx Current For a Rusty Rail Surface Scenario

In Figure 42, at T10 the actual rear-of-train location passes the beginning of the rusty surface zone and loss of shunt occurs. The system then starts to use the end of the rusty surface zone location (L7) as a false rear-of-train location, until time T11 when the actual rear-of-train location passes the end of the rusty surface zone replacing the false rear-of-train location. This is because the current gap caused by the rusty surface is the same as the normal current drop between L6 and L7 without the rusty surface.

If this current gap is more significant than a pre-set threshold, the system would exit VB mode. In the VBTC system, this threshold current can be converted into a length within the block called Lthreshold and the length of a rusty surface can be called L_{rusty}, while the safety buffer/margin length can be called L_{safety}. The following statement then can be addressed:

- If Lthreshold < Lrusty, this system can be considered safe because the current drop caused by the rusty surface will trigger the system to exit VB mode.
- If Lthreshold > Lrusty but Lsafety > Lrusty, this system can be considered safe because the safety buffer will cover the false Clear.
- If Lthreshold > Lrusty > Lsafety, this system is considered unsafe due to the potential false Clear of the VB section. This risk should be very low, however, because if the track circuit is accurately calibrated, Lthreshold will equal Lrusty.

For a new VBTC product introduction, testing is recommended to collect data about the relationship between these three parameters.

9.6 Rail Metal Inconsistency Causing Inaccuracy of Location Detection

In VBTC basic theory, the rail is considered a homogeneous metal, which means that the rail resistance increases linearly with rail length. However, in an operational environment, some defects could potentially affect the consistency of rail resistance. If such a defect occurs over a very short amount of time (e.g., a partial rail break occurring under a passing train), it could temporarily affect VBTC location detection accuracy until a few subsequent train runs have occurred to allow the system to recalibrate.

The mitigation for this problem can be proposed as follows:

- In a clear track block, if the resistance is increased or decreased beyond a pre-set threshold within a short amount of time or when compared before and after a single train pass-through, then the system should exit the VB mode.
- When the analog Tx current measured from the device indicates that there is a certain current gap (like that shown in Figure 42) and this gap is beyond the pre-set threshold, then the system should exit the VB mode.

Note, however, that some normal track features can also cause discontinuities or non-linearities in rail impedance and these should be mitigated by self-calibration functionality in the VBTC devices.

10. Potential Enhancements for VBTC

As the VBTC concept is very early in its life cycle, there are potential enhancements that could be applied to potentially provide better system performance and mitigate or eliminate some of the issues discussed in the previous section.

10.1 Out-of-Band Communication Between VBTC Wayside Devices

Since the VBTC system described in this ConOps operates based on the foundation of DC-coded track circuits, similar characteristics are shared between the two concepts.

When a physical track block is unoccupied, devices from each end of the track can communicate with each other using track codes through the rail. When a physical block is shunted, devices from each end of the track cannot communicate with each other.

An "out-of-band" (e.g., wireless or wired) communications link could be installed between each pair of VBTC devices so they can exchange information when the track between them is occupied. Information exchange between devices could form a VBTC network that would be the foundation for some enhanced functions introduced in the following sections. It might be possible to use existing PTC radios or backbone connections at WIUs for this purpose.

Figure 43 shows how a linear topology network could be formed if a non-track code based communication system was set up between VBTC devices. The information exchanged within the network could include dynamic coordination of which VBTC device transmits status for each VB, train-related information (introduced in a later subsection), broken rail detection, etc.

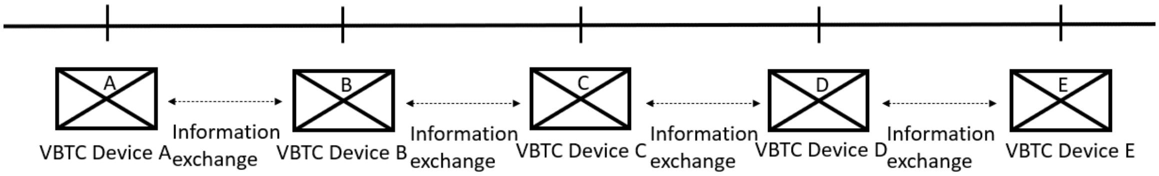


Figure 55. VBTC Information Network

10.2 Virtual Block Signal as Controllable Absolute Signal (Control Point)

As discussed in Section 5.3, most virtual signals are used as intermediate signals in the basic VBTC system. These are automatic signals that are not controllable by the dispatcher.

One VBTC architectural variant is to configure all virtual signals in a region to be used as absolute controllable signals (i.e., control points). The potential benefits of this architectural variant are as follows:

1. The dispatcher can have more precise control over train movements. In CTC with conventional track circuits, the dispatcher can typically only affect train movements at powered turnouts, interlockings, and a limited number of other locations where there is adequate financial justification for installing expensive wayside CP logic and IJs. With controllable VBTC signals, the dispatcher can exert much finer resolution control of train movements, down to the virtual block level, at significantly lower cost than having conventional CPs at each of these locations. Excess train spacing can be reduced to one virtual block length for certain operations (e.g., parking a train).

2. With each VBTC signal used as an absolute signal instead of an intermediate permissive signal, collisions associated with a following train entering an occupied block under RSR can be avoided as long as the dispatcher does not give the following train an authorization to pass signal at Stop.

CPs at virtual signals can use conventional CAD-Wayside communication (i.e., code line) protocols to communicate with the CAD system. The code line data load could increase substantially with the additional CPs.

10.3 Double-layer VBTC System

The double-layer VBTC architecture is considered an advanced VBTC system compared to the single-layer VBTC system discussed in most of this document. In the double-layer system, a train's onboard would require modifications to simultaneously use statuses originating from VBTC devices both ahead of and behind the train reporting on the same virtual block to address related issues. If the VBTC network discussed in Section 10.1 is available, the onboard can obtain this information through a single VBTC location. A similar architecture is suggested in patent US 10,894,550 B2.

Another way to allow an onboard to simultaneously use status from both ends of a track circuit for the same virtual block without requiring modification to the onboard is for WIUs to transmit Hazard Detection indications rather than Signal indications in the Device Status Code field of WSMs. The ITC PTC onboard accepts dual reports about the same block in this case.

Figure 44 shows an example of a double-layer VBTC system currently unoccupied. An incoming train will enter Physical Block 1 at Device A and exit at Device B.

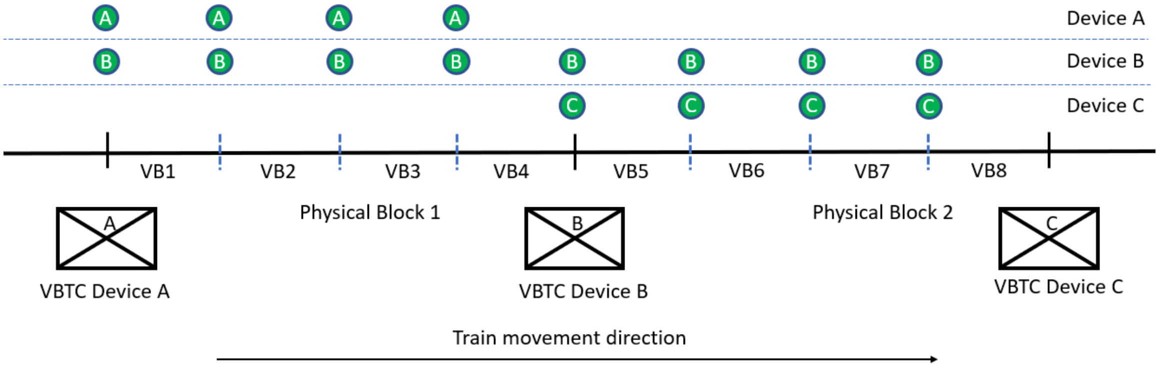


Figure 56. Example of a Double-layer VBTC System

10.3.1 Double-layer System with an Out-of-Band VBTC Network

In a double layer VBTC system, if an out-of-band VBTC network exists at the wayside, each VBTC wayside device can choose to broadcast VB status based on information collected from both ends of each physical block so that the onboard only receives data from one device (e.g., the entry-side device) for each VB.

10.3.2 Double-layer VBTC Implementation

The double-layer VBTC is considered advanced compared to the basic VBTC architecture. Many potential enhancement functions introduced in the following sections are based on double-layer VBTC. However, to implement this architecture, the onboard system and current WSM protocol may require significant modifications.

10.4 Train Length Estimation for Guiding Operation and Protection Against Pull-Apart

In the VBTC system, since the front-of-train location and rear-of-train location can be detected by VBTC devices, the train length can be calculated by analyzing the collective information. Based on different system architectures, there are multiple solutions for estimating train length.

- Based on the number of virtual blocks: If train length estimation does not require high accuracy, the train length can be estimated based on the number of virtual blocks occupied and virtual block lengths identified within the track database. Also, this occupied virtual block number should have a maximum and minimum range due to train HOT and EOT location (e.g., a three-block long train may occupy two full virtual blocks and part of two other virtual blocks, therefore for this train, this maximum value will be 5, and the minimum value will be 3). This level of train length estimation can be achieved with a double-layer VBTC or VBTC network.
- Based on analog data: If train length estimation requires higher accuracy, then train length may be estimated based on the detected front-of-train and rear-of-train location with a specific buffer. This level of train length estimation requires a VBTC network between devices to exchange necessary train shunt location data for calculation. The amount of accuracy improvement is dependent upon the product design/implementation and may not be significantly greater than that achievable with the method described above.

With the train length estimation feature, the following enhancement function can be achieved:

- With train length information from the wayside devices, the onboard can compare the estimated train length information received with current train PTC onboard consist data; if the two sources of train length data differ significantly, a train separation can be detected. In addition, for wayside devices operating with an out-of-band VBTC network, if the estimated distance between front-of-train and rear-of-train location for a particular train is growing longer by more than a threshold amount, then a train separation warning can be triggered to provide pull-apart protection, and the onboard can ignore this message if the train separation is intentional.

10.5 Train Speed Estimations

Based on the principles introduced in previous sections, the VBTC system can estimate the shunting item speed within the block. Since the distance from the shunting item to the wayside device is known by the system, the VBTC device can calculate the shunting item moving speed based on the location change vs. time.

This function can provide an extra layer of protection for some locations, such as highway crossings and portable bridges.

11. Summary and Conclusions

VBTCs are still in the early stages of their product life cycle, with the expectation they will increase the line-of-road capacity and reduce headways in train operation.

This ConOps document discussed the basic principles of the VBTC concept, some performance-related features, basic message architecture, some system level limitations, and potential advanced architectures with enhancement features. These topics are not limited to specific products or prototypes but focus on the VBTC system as a technology concept. Some limitations may already be resolved or mitigated in some products or prototypes developed by suppliers.

As part of the VBTC assessment project research, some characteristics addressed in this ConOps document were field tested, and test results can be found in the main report to which this Appendix document is attached.

The future of VBTC-related research can focus on further testing (e.g., in additional environmental conditions) and developing standardized system requirements and interface control documents, especially for the development of some advanced features.

Abbreviations and Acronyms

Acronym	Definition
ABS	Automatic Block Signaling
CAD	Computer-Aided Dispatch
CP	Control Point
EO-PTC	Enhanced Overlay PTC
EOT	End-Of-Train
FMB	Full Moving Block
GPS	Global Positioning System
HOT	Head-Of-Train
IJ	Insulated Joint
ITC	Interoperable Train Control
O-PTC	Overlay PTC
QMB	Quasi-Moving Block
VB	Virtual Block
VBTC	Virtual Block Track Circuit
WIU	Wayside Interface Unit
WSM	Wayside Status Message

Appendix B.
Virtual Block Track Circuit Assessment Test Report

Contents

1. Introduction

As part of the virtual block track circuit (VBTC) assessment project, a set of VBTC devices were acquired and tested by a research team at Transportation Technology Center, Inc. (MxV Rail). The field tests occurred on the Railroad Test Track (RTT) at the Federal Railroad Administration's Transportation Technology Center (TTC). These tests evaluated the device performance and verified system characteristics.

1.1 Purpose

The purpose of this document is to provide background information about the VBTC equipment and test environment, explain the calibration process for this VBTC system, and present the records of performed test cases, test results, analysis, and findings.

1.2 Scope

This document describes the test approach and test results pertaining to a commercially available VBTC product; specifically, the Alstom ElectroLogIXS/EC5. The application for this product was based on the needs of the testing environment and the tests. Tests were performed under a limited set of operational and environmental scenarios.

1.3 Document Overview

The document is organized as follows:

- Section 2 provides a VBTC background and introduction to the ElectroLogIXS/EC5 device used in the testing.
- Section 3 introduces the test track for this project and other preparations for the field test.
- Section 4 provides a summary of the test cases and details of the test matrix.
- Section 5 introduces the calibration process and the discoveries made during this process.
- Section 6 describes test cases in detail along with the test result records and initial analysis for each test case.
- Section 7 presents the summary, findings, and conclusions of this field test.

2. VBTC Background and Testing Device Overview

This section introduces the basic concept and hardware model for the VBTC system, the ElectroLogIXS/EC5 devices, and the application used for this test.

2.1 VBTC Basic Hardware Model and Principles

The basic VBTC system can be understood by the simplified model shown in Figure 1. Two VBTC devices serve as transceivers, working in coordination under design time cycles and measuring the transmit current (TxC) and receive current (RxC).

The VBTC system identifies the virtual block that is closest to the device as “VB1” and farthest as “VB4.” In Figure 1, virtual blocks are numbered in order from VB1 to VB4 from the perspective of VBTC Device A.

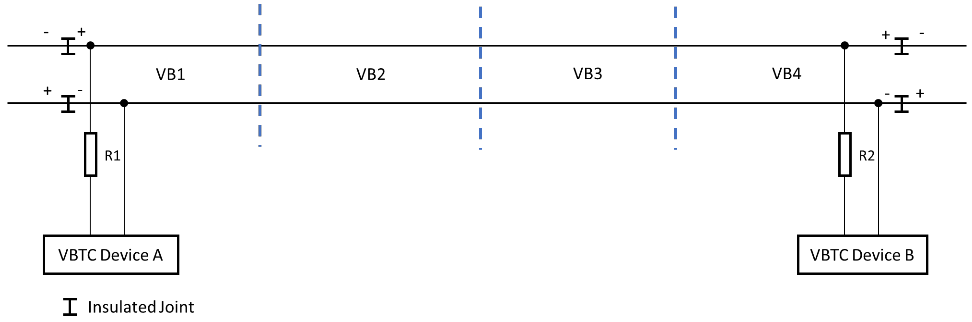


Figure 57. Simplified VBTC System Hardware Model

When a train enters the block from the side closest to VBTC Device A, performs constant speed movement, and exits the block from the side closest to VBTC Device B, the TxC current is measured from VBTC Device A as shown in Figure 2. The time point T1 is the moment the first axle of the train enters the block and the time point T2 is the moment the last axle of the train enters the block. The end of the train then proceeds further within the block between T2 to T3. The location of the end of the train is related to the TxC current measured. The primary change in resistance between T2 and T3 is the track rail resistance between the train and VBTC Device A. Thus, the location can be calculated using that measurement and other information collected (e.g., wayside resistance of the bungalow, track circuit output voltage, etc.).

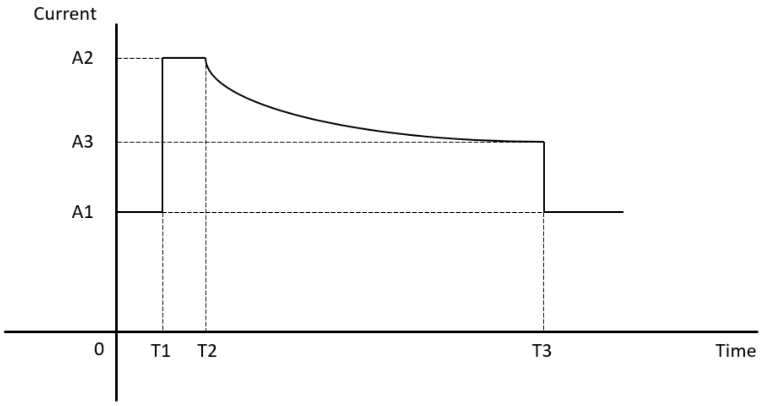


Figure 1. Illustration of the TxC Measurement from VBTC Device A

A detailed explanation of VBTC principles is introduced in Appendix A, Section 2.

2.2 ElectroLogIXS/EC5 Device

The VBTC system selected for testing in this project is based on the Alstom ElectroLogIXS/EC5 system. This is a DC-coded track circuit system with enhanced software to perform VBTC functionality. In addition, a component VTI-2E module was installed within the chassis to measure the TxC current and RxC current.

The VBTC feature for the ElectroLogIXS/EC5 device is a new function installed on the EC5 device as compared to conventional EC5 track circuit functionality.

2.3 EC5 Device Application Code

In this series of tests, Alstom provided application code with minimum functionality that supports VBTC system operation under the prepared field test environment.

This application included the following characteristics based on the test needs:

- **Track code:** Basic track codes to be used to indicate track occupancy status and set up direction for train movement
- **Direction stick:** Used for setting up the direction of movement based on the track code from the adjacent track section or entry track circuit
- **Track status:** Used to indicate the virtual block occupancy status for each individual virtual block after the system is fully calibrated, as well as the occupancy status for the whole physical block
- **VB mode status**: Used for indicating when the VB mode is active or inactive for each train movement (VB mode also referred to as VBTC mode in this document)
- **Broken rail indication:** Used for showing the track integrity status

The application configuration supported two physical track circuit blocks (eight virtual blocks) and two entry track circuit environments.

2.4 ElectroLogIXS/EC5 Data Log and System Log Overview

In this test, the team used two critical resources for obtaining the system test results: the data log record and the system log record. The vital system events were recorded in the system log and all status changes were recorded in the data log. All the logs were time stamped and set coordinated to Universal Coordinated Time (UTC).

Below is an example of the system log:

```
06-01-22 17:42:18 B:VBTRACK 03204 Slot 1 Track 1 (LTK_VB) Invalid Inbound Move for
Calibration - Far Shunt TxC
        time_elapsed: 412.2
        far_shunt_txc: 2051 mA, far_txc: 1951 mA (too low)
06-01-22 17:35:08 A:VBTRACK 04650 Slot 1 Track 1 (LTK_VB) Location Disabled - Far
Entry Threshold Not Met
        far_entry_min: 1858, far_entry_max: 2044
```

pulses: 2079 2076 2068 2059 2049 (newest to oldest)

Below is an example of the data log:

```
06-20-22 21:12:08 Vital Recorder Entry
L_VB_ACTIVE =T L_VB_TRK_INT=T L_VB_VB1_OCC=T L_VB_VB2_OCC=T
L_VB_VB3_OCC=T L_VB_VB4_OCC=T LTKI1=T
06-20-22 21:12:00 Vital Recorder Entry
L_VB_TSTGRNT=T
06-20-22 21:12:00 Vital Recorder Entry
L_VB_UNSHUNT=T
```

2.5 Wayside System Data Management Module and Grafana

Based on the test needs, a wayside system data management module (WSDMM) was added to ElectroLogIXS/EC5 devices and used to obtain and record the TxC and RxC for each device.

The data collected was visualized in Grafana, a multi-platform, open-source analytics and interactive visualization web application.

Figure 3 illustrates the Tx current (yellow dots), and the Rx current (green dots). In this figure, several train movements can be observed:

1. Train movement 1 (outbound): From the device location to the far side, as Tx current is decreasing because the track rail resistance within the circuit loop is increasing
2. Train movement 2 (inbound): From the far side to the device location
3. Train movement 3 (outbound, stop, inbound): From the device location, stopping for some time and then reversing out of the block from the device location
4. Train movement 4 (outbound, stop, inbound, stop, outbound): From the device location, changing movement direction within the physical block, exiting from the far side
5. Train movement 5 (inbound): From the far side to the device location

Figure 2. Screenshot of Track Current Data After Visualization by Grafana

Note that the green dots representing the RxC are covered by the yellow dots representing the TxC in the figure, and when the physical block is occupied, the green dots are not shown because the Rx current is near zero.

3. Testbed and Related Preparation

This section discusses the preparations for the field testing and key equipment used in this project. Field testing was performed on the RTT at the TTC.

3.1 Test Track

The testbed was located on the RTT, a 13.5-mile loop track comprised of welded rail. The test runs were conducted on a section from post R34.5 to R70.5, including two 11,880-foot physical block sections. Figure 4 illustrates the original track layout.

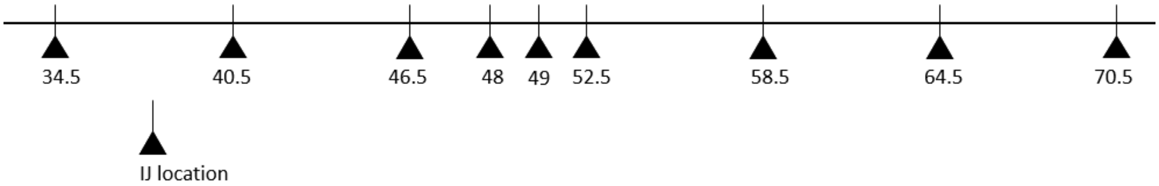


Figure 3. Original Track Condition for Selected Test Track

Based on the test cases and the track conditions, most insulated joints (IJs) between R46.5 to R64.5 had jumpers welded across them to create two 11,880-foot (2.25 miles) test track sections for VBTC. Figure 5 shows the modified track configuration. Additionally, EPIC track circuits (supplied by Alstom) were used as approach track circuits to set up a direction stick for entry into the VBTC test section. The track circuits were installed from post R64.5 to R70.5 and post R34.5 to R40.5.

In the application code, and in all the log records from the VBTC devices used in testing at TTC, the R40-R52 track section (Physical track 2) is referred to as the “L track” and R52-R64 track section (Physical track 1) is referred to as the “R track.” The same designations are used throughout this document.

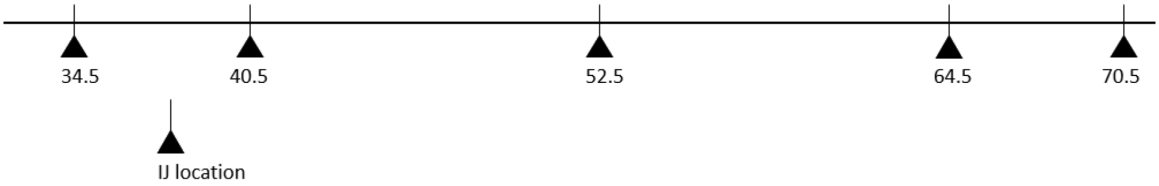


Figure 4. Track Configuration After Modification

3.2 Key Location GPS Coordinates and Track Length Measurement

In an ideal scenario, the VBTC track system would equally divide each physical block into four virtual blocks. The physical block track length value is key information that needs to be configured into the system’s initial settings.

The team measured GPS coordinates for the following key locations:

- R64, R52, and R40 IJ locations
- Ideal virtual block boundary for each physical block

The track length between the R64 IJ and the R52 IJ is 11,880 feet. The track length between R52 IJ and R40 IJ is 11,880 feet.

3.3 Bungalow Setup

To provide housing for the track circuit equipment, three bungalows were set up at the R40, R52, and R64 locations. The R64 and R40 bungalows had the same equipment setups, each containing one set of VBTC equipment and one set of EPIC track circuit equipment for the entry (i.e., approach) track. The R52 bungalow had one set of VBTC equipment which served both VBTC track circuit sections – L track and R track. Figure 6 and Figure 7 show two views of the bungalow setups.

Figure 5. R64 Bungalow Inside View

Figure 6. R52 Bungalow Inside View

Figure 8 shows the VBTC track layout.

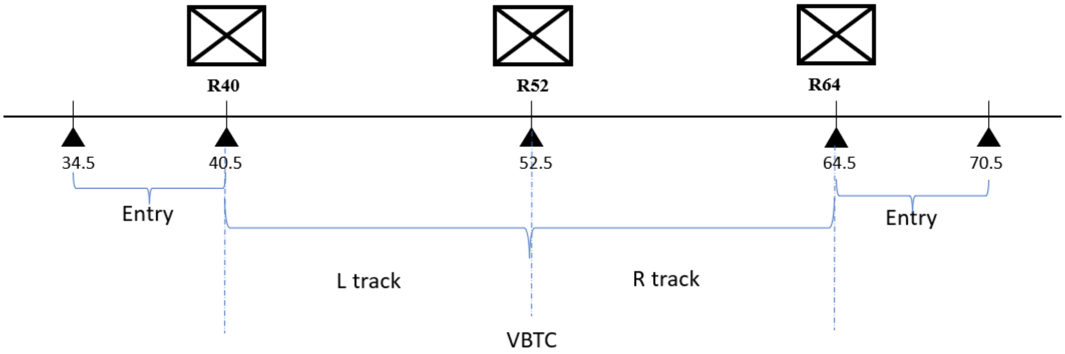


Figure 7. VBTC Test Track Layout

3.4 Train Consists

Most of the VBTC tests were performed with a train consisting of a single locomotive with nine freight rail cars (six loaded, three unloaded). The length between the first axle of the locomotive and the last axle of the rail car was 503 feet. The train was able to achieve the speed required for testing. In addition, a GPS device was installed on the locomotive, as shown in Figure 9 and Figure 10, to measure the real-time GPS data for some test cases.

Figure 8. Diagram showing GPS Location within the Train Consist

Figure 9. Test Train Consist

3.5 Wet Track Preparation

Wet track conditions were required in some test cases. The team used a single locomotive towing a water tank car filled with water (capacity 20,643 gallons), as shown in Figure 11, on the track section between R52 and R40. During the process, the valve of the tank car was opened, and the train moved at a constant speed of 20 mph back and forth within the selected track section. Figure 12 shows the wet track following this process. Further details on wet track testing are available in Section 6.12 of this Appendix.

Figure 10. Train Consist Used for Wet Track Preparation

Figure 11. Wet Track

3.6 Broken Rail Preparation

For test cases in which a simulated broken rail was required, a mechanism to simulate the broken rail environment was set up at R46, as shown in Figure 13, Figure 14, and Figure 15. For normal test scenarios, a jumper bond was welded across the R46 IJ. For broken rail-related tests, based on the test requirement, the mechanism was triggered in real time as a train passed over R46 to simulate a rail break occurring under a train, which is the most common situation in which a rail break occurs.

The rail break mechanism consisted of a clamp applied across a cut in the middle of the jumper wire. The clamp was attached to a rope so that a team member could pull the rope to remove the clamp and cause a rail discontinuity to simulate a rail break from a safe distance as a train was passing over R46. Other options to create a precisely timed rail break event were considered (e.g., a relay), but they presented too much resistance given the sensitivity of the track circuit. The track circuit resistance remained as it was before the mechanism was introduced.

Figure 12. Broken Rail Trap During Normal Test Scenarios

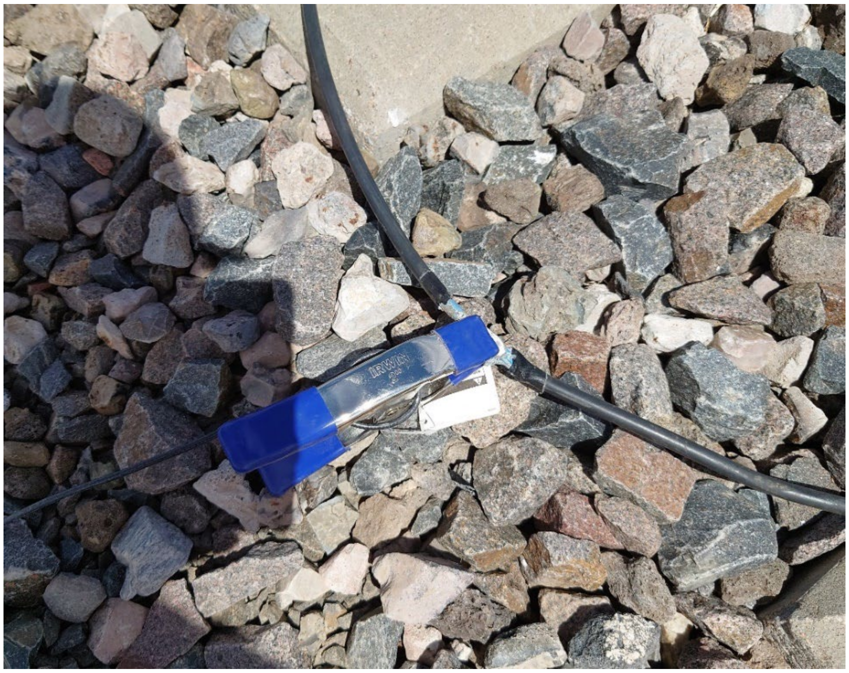


Figure 13. Trap (Clamp) for Broken Rail Scenario (Preparation)

Figure 14. Clamp Mechanism for Broken Rail Test Scenarios (Disconnected)

4. Summary of Test Cases and Test Matrix

This section introduces the field test cases performed and discusses the purpose of each test case.

4.1 Test Case Groups

The test cases were divided into the following groups:

1. **Basic performance tests**: In this test group, the basic performance of the VBTC system was tested, including normal constant speed train movement under the default VB Scale Factor setting and different VB Scale Factors, train movements with changing speed within the VBTC block, and other scenarios.
2. **Operational environment scenario tests:** In this test group, some operational scenarios were simulated including a power outage for the devices, broken rail scenarios, a pull-apart test, and a double occupancy test.
3. **Wet track test:** In this test group, the selected track section was artificially wetted with water. Test cases performed in this test group were used to compare with similar test cases under normal (i.e., dry) conditions.

The summary of test cases for each group are presented in the test matrix and details for each test case and test results are presented in Section 6 of this Appendix.

4.2 Test Case Matrix

Table 1 shows the test cases in brief and the test group to which each test belongs. Detailed test procedures and test results are presented in Section 6.

Table 14. Test Case Matrix

Test No.	Test Group	Test case name	Test case description
1	Basic performance test	Basic system operation test	Basic constant movement
2	Basic performance test	System detection accuracy under same VB Scale Factor	Basic constant movement at various speeds under same VB Scale Factor
3	Basic performance test	System detection accuracy under different VB Scale Factors	Basic constant movement with various VB Scale Factors
4	Basic performance test	Changing speed test	Acceleration test within VBTC section
5	Operational scenario test	Single locomotive test	Single locomotive constant speed test
6	Operational scenario test	Pull-apart test	Operational pull-apart scenarios (train was decoupled in the middle)
7	Operational scenario test	Double occupancy within single block test	A double occupancy event within the same physical block
8	Operational scenario test	Changing movement direction within single block	A movement direction change event in operational scenario within same physical block

Test No.	Test Group	Test case name	Test case description
9	Operational scenario test	Broken rail test with multiple scenarios	Broken rail test with different scenarios including broken rail caused by train and spontaneous broken rail
10	Operational scenario test	Power outage test	A field power outage event to verify system performance
11	Operational scenario test	Loss of shunt test due to simulated rusty surface	Simulated rusty surface within middle of block and a loss of shunt event
12	Wet track test	Wet track preparation	Preparation for wet track by distributing water from tank car; data was collected during the train movement
13	Wet track test	Constant speed test	Basic constant movement test with wet track
14	Wet track test	Broken rail test	Broken rail test with different scenarios under wet track similar to Test Case 9
15	Wet track test	Ballast condition test	Test ballast condition change with track from wet to dry

5. Calibration Process

Every EC5-based VB track circuit must be calibrated by running 50 valid train movements through the monitored physical block before the VBTC mode can be activated. Each device determines its own calibration curve (using 50 valid trains) for each track independently.

5.1 Calibration Requirements from the System

According to instructions received from the supplier, for a move to be considered a valid calibration train movement, the following requirements must be met:

- Must be a through move
- The average speed of the complete move across the entire track circuit must be greater than 15 mph
- No stopping or reversing during the movement
- Must use minimal acceleration (decelerating or constant speed trains are also valid, as are trains with limited acceleration)

When a train completes a movement in a VBTC track section and fully exits a physical track circuit block, the system log provides the analysis result, indicating whether the train movement was considered valid. For a train movement that is considered invalid, the reason for calibration failure is also presented in the system log. Below is an example log:

```
Slot 1 Track 2 (RTK_VB) Invalid Outbound Move for Calibration - Acceleration
```

When the VBTC device reaches 50 valid calibration train movements with the VBTC function enabled, the following time stamped record appears in the system log followed by the calibration data matrix:

```
Slot 1 Track 1 (LTK_VB) Initial Calibration

cal_bias: most sensitive
```

5.2 Calibration Train Movement Within Selected Test Track Section

The RTT segment used for VBTC testing included two physical tracks with three independent EC5 devices. The R52 location with a single EC5 device used two independent calibration processes, one for the R64 to R52 section (R track) and one for the R52 to R64 section (L track), as shown in Figure 16.

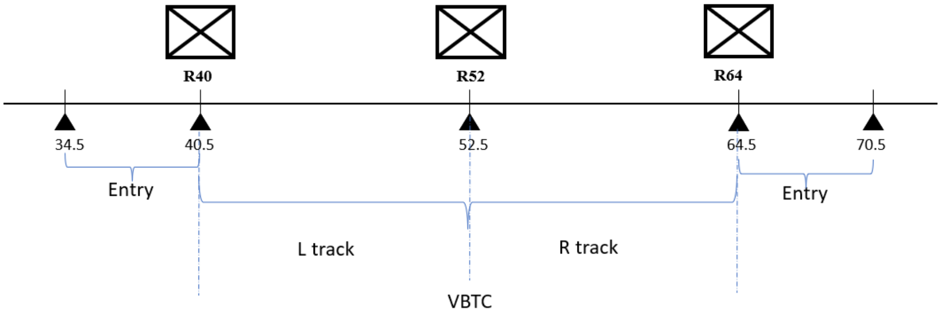


Figure 15. Diagram of the Test Track Layout

Due to the limitation of using EPIC track circuits as entry tracks for the VBTC test section, the entry speed for each end of the VBTC test section could not exceed 45 mph. The train consist for calibration movement was a single locomotive with nine rail cars. As the calibration process required constant speed movement within a single physical block that cannot be below 15 mph, the train speed used in the calibration process was between 20 mph and 40 mph. Figure 17 shows an example of a calibration train movement.

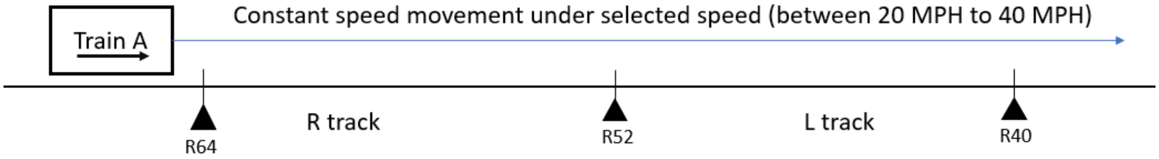


Figure 16. Diagram of Calibration Train Movement Example

5.3 Analysis of Failure Cases During Calibration Movements

There are multiple reasons a train movement would be considered a failure from the calibration perspective, since different devices collect calibration data independently and the progress is different for each device and each section for the same device. There are two major reasons train movement may be recorded as invalid during the calibration process:

1. "Invalid Outbound Move for Calibration - Far Shunt TxC" or "Invalid Inbound Move for Calibration – Far Shunt TxC" – This indicates that the far side shunting current was beyond the range of preset data when the VBTC system was initiated. The preset data was replaced with calibration data when the system was calibrated.
2. "Invalid Outbound Move for Calibration – Acceleration" or "Invalid Inbound Move for Calibration – Acceleration" – This indicates that acceleration was detected for this train move so the movement could not be used as a valid calibration movement.

5.4 VBTC System and VB Layout after Calibration

After calibration, each device has a different layout for VB blocks, as the same virtual block can be named differently by each device, as shown in Figure 18.

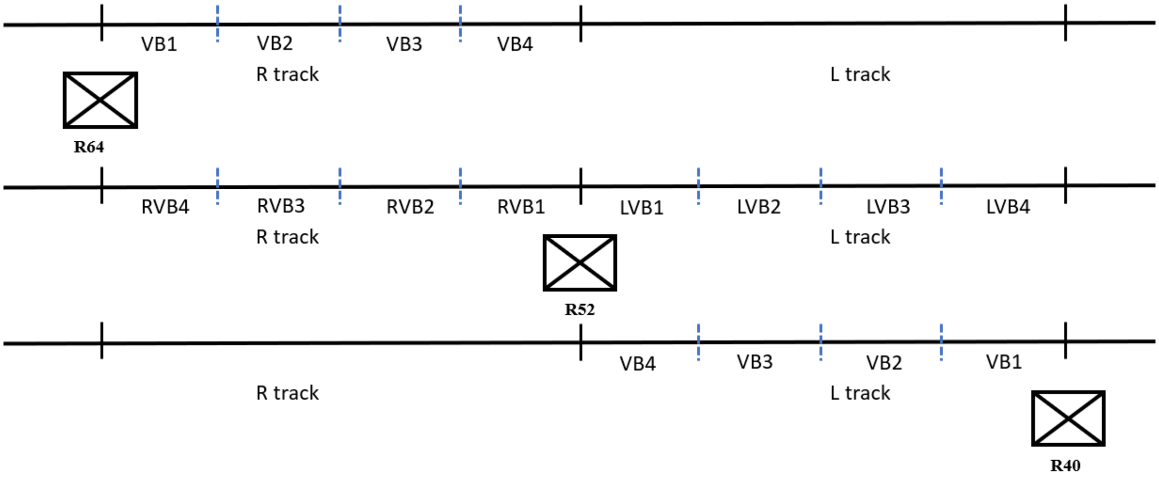


Figure 17. Diagram of VB Layout for Each VBTC Device

For each VBTC device, the track circuit status used to observe the virtual block performance in this field test included the following:

1. Occupancy status for physical block (this status also used for tracking loss of shunt in some test cases)
2. Occupancy status for each individual virtual block
3. The status that indicates whether the system VBTC mode is active
4. The system log for broken rail detection and location reports
5. Other statuses related to certain test aspects

Each of the status log records was time stamped with UTC time.

6. Detailed Test Cases and Results Analysis

This section presents the field test cases in detail, including the purpose of each test case, the detailed test procedure, the record of test results, and initial analysis. Note that all the test record times shown in the tables are UTC and the current (TxC and RxC) recording times are Mountain Daylight Time (MDT).

For most test cases, a table with virtual block status is shown. In those tables, "T" indicates that the track block status is Clear and "F" indicates that the track block status is occupied. R64, R52, and R40 indicate the bungalow locations. The rest of the posts indicate other salient locations.

The titles for most of the test case tables follow this format: "Data log location, Train movement direction." For example, "R64 Data log record, R64 to R40" means this is the data log record obtained from the VBTC device at R64 and the train movement is from R64 to R40. For data records related to R52, "RVB" means the VB in the R block (R64-R52 section) and "LVB" means the VB in the L block (R52-R40 section).

It should be noted that in many of the tables below, status VB4 for an outbound train move does not clear until a few seconds after the train leaves the physical block. This is due to the code design on which VB4 status clearing is based (i.e., Code 1 (occupancy) clearing) while the VB1, VB2, and VB3 statuses Clear based on the transmit current into the end of train (EOT).

Some of the test cases refer to a parameter known as the "VB Scale Factor." Increasing this parameter allows for widening the allowable operational variance for virtual block mode, but also increases the VB safety buffer.

6.1 Basic System Operation Test

6.1.1 Purpose

This test was performed with constant speed train movement within the test section to obtain a record of the basic system operational behavior to be used as the baseline for comparison with other test cases, and to verify that the system was functioning properly.

6.1.2 Test Case Procedures

The train consist used in this test comprised nine rail cars and a single locomotive, which performed the baseline constant speed train movement within the test section. The VB Scale Factor was set to 0 percent (default).

In this test, illustrated in Figure 19, the train entered R64 at a speed of 20 mph and maintained constant speed until exiting the R52 section. The same process was repeated from R52 to R64.

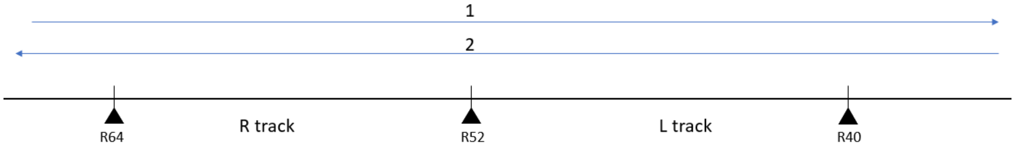


Figure 18. Test Case 1 Train Movement Diagram

The data recorded for this test was obtained from the ElectroLogIXS/EC5 device data logs and system logs.

6.1.3 Recorded Test Results and Initial Analysis

Results are provided by device location, train movement, and corresponding VB status in Table 2, Table 3, Table 4, Table 5, Table 6, and Table 7.

Table 15. R64 Data Log Record, R64 to R40

Location	R64	**Begin**	R64	Note		
Train speed	20 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block, VB1-4 occupied	15:30:41	F	F	F	F
2	VB1 clear	15:33:35	T			
3	VB2 clear	15:35:17		T		
4	VB3 clear	15:36:55			T	
5	Train exits the block	15:37:39				
6	VB4 clear	15:37:46				T

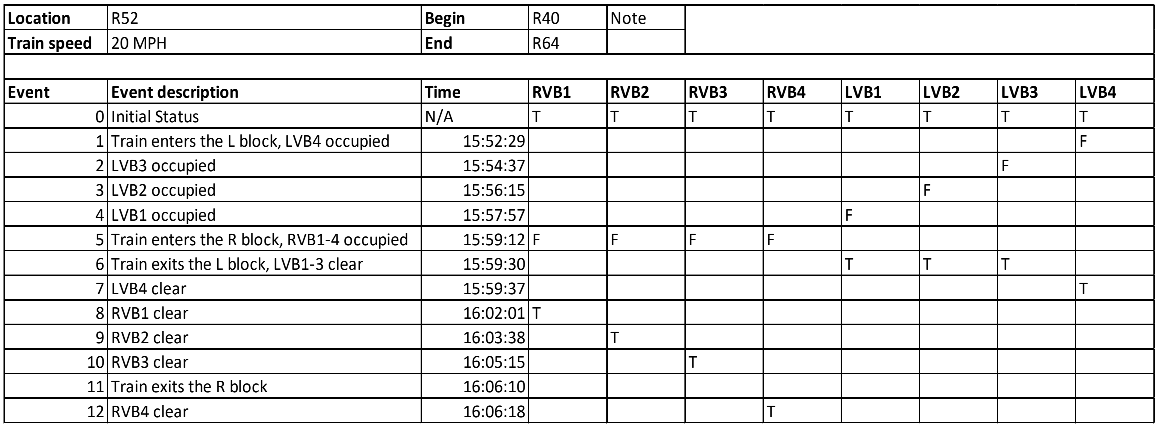
Table 16. R64 Data Log Record, R40 to R64

Location	R64	**Begin**	R40	Note		
Train speed	20 MPH	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block, VB4 occupied	15:59:14				F
2	VB3 occupied	16:01:26			F	
3	VB2 occupied	16:03:07		F		
4	VB1 occupied	16:04:38	F			
5	Train exits the block	16:06:09				
6	VB1-VB3 clear	16:06:13	T	T	T	
7	VB4 clear	16:06:17				T

Table 17. R52 Data Log Record, R64 to R40

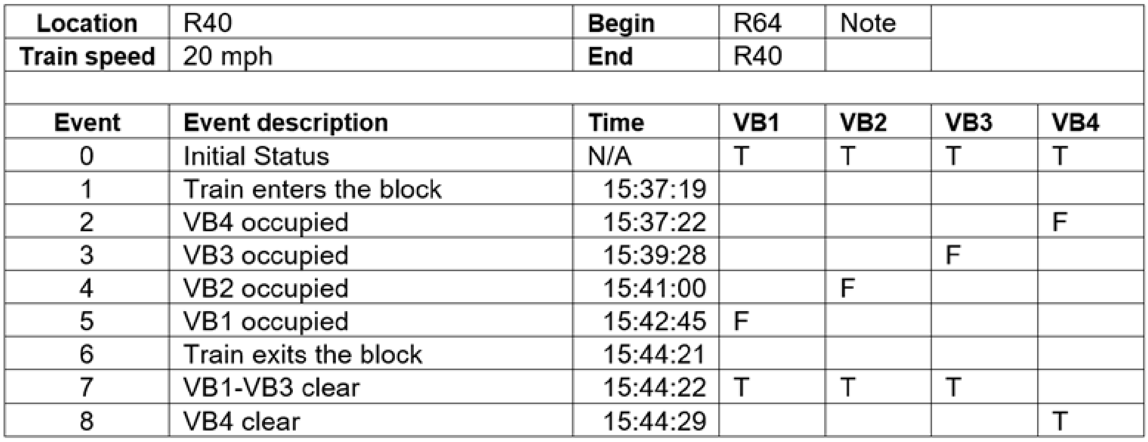
Location	R52	**Begin**	R64	Note						
Train speed	20 MPH	**End**	R40							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the R block	15:30:40								
2	RVB4 occupied	15:30:43				F				
3	RVB3 occupied	15:32:52			F					
4	RVB2 occupied	15:34:34		F						
5	RVB1 occupied	15:36:03	F							
6	Train enters the L block, LVB1-4 occupied	15:37:21					F	F	F	F
7	Train exits the R block	15:37:38								
8	RVB1-3 clear	15:37:42	T	T	T					
9	RVB4 clear	15:37:46				T				
10	LVB1 clear	15:40:27					T			
11	LVB2 clear	15:42:09						T		
12	LVB3 clear	15:43:46							T	
13	Train exits the L block	15:44:20								
14	LVB4 clear	15:44:28								T

Table 18. R52 Data Log Record, R40 to R64



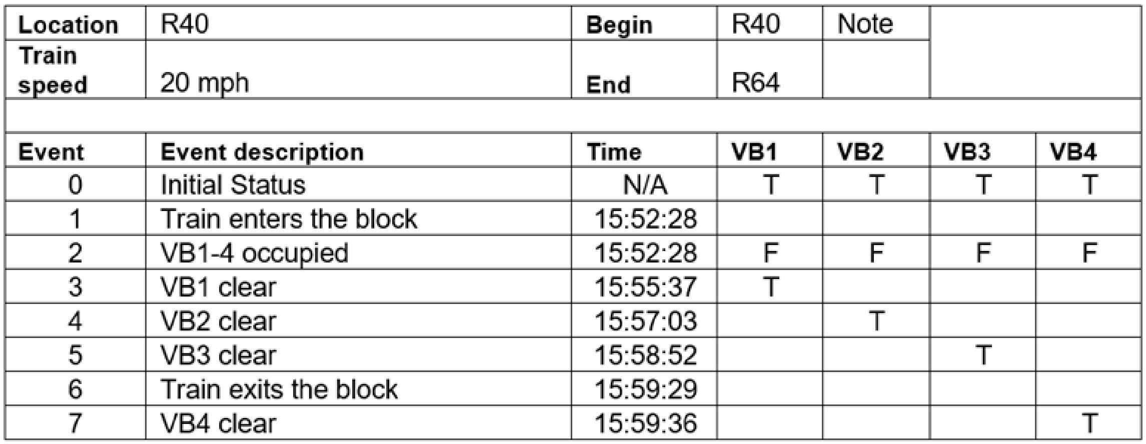
Location	R52	**Begin**	R40	Note						
Train speed	20 MPH	**End**	R64							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the L block, LVB4 occupied	15:52:29								F
2	LVB3 occupied	15:54:37							F	
3	LVB2 occupied	15:56:15						F		
4	LVB1 occupied	15:57:57					F			
5	Train enters the R block, RVB1-4 occupied	15:59:12	F	F	F	F				
6	Train exits the L block, LVB1-3 clear	15:59:30					T	T	T	
7	LVB4 clear	15:59:37								T
8	RVB1 clear	16:02:01	T							
9	RVB2 clear	16:03:38		T						
10	RVB3 clear	16:05:15			T					
11	Train exits the R block	16:06:10								
12	RVB4 clear	16:06:18				T				

Table 19. R40 Data Log Record, R64 to R40



Location	R40	**Begin**	R64	Note		
Train speed	20 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	15:37:19				
2	VB4 occupied	15:37:22				F
3	VB3 occupied	15:39:28			F	
4	VB2 occupied	15:41:00		F		
5	VB1 occupied	15:42:45	F			
6	Train exits the block	15:44:21				
7	VB1-VB3 clear	15:44:22	T	T	T	
8	VB4 clear	15:44:29				T

Table 20. R40 Data Log Record, R40 to R64



Location	R40	**Begin**	R40	Note		
Train speed	20 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	15:52:28				
2	VB1-4 occupied	15:52:28	F	F	F	F
3	VB1 clear	15:55:37	T			
4	VB2 clear	15:57:03		T		
5	VB3 clear	15:58:52			T	
6	Train exits the block	15:59:29				
7	VB4 clear	15:59:36				T

In this test, the VBTC system functioned properly for all VBTC devices and satisfied the basic requirements to detect each virtual block's occupancy status. Notice that the "VB4 Clear" status normally appears around 7 seconds after the physical block becomes clear.

6.2 System Detection Accuracy for the Same VB Scale Factor

6.2.1 *Purpose*

Train control system performance (e.g., headways, traffic capacity) in revenue service is impacted by the accuracy of VBTC's train location detection and highly affected by the safety buffer behind the rear of the train. Therefore, it is important to determine the amount of safety buffer that the VBTC product applies in field testing.

6.2.2 *Test Case Procedures*

The train consist comprised nine rail cars and a single locomotive and performed a basic constant speed train movement within the test section.

In this test, as shown in Figure 20, the VB Scale Factor was set to 0 percent, the default setting for the system. System performance with different train speeds was also tested. To perform this test, a train equipped with GPS on its front entered the R64 location at a selected speed and maintained constant speed until exiting the R52 section. The same process continued from R52 to R64.

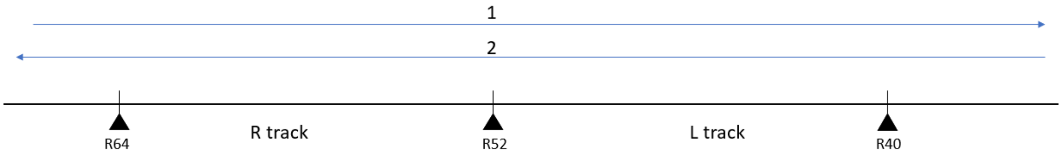


Figure 19. Test Case 2 Train Movement

The data recorded for this test was obtained from the ElectroLogIXS/EC5 device data logs and system logs, and train location was compared with pre-measured ideal virtual block boundary locations and GPS data. The distance from each ideal virtual block boundary to the rear-of-train location was used to determine the system detection accuracy results.

6.2.3 *Recorded Test Results and Initial Analysis*

6.2.3.1 *Test Run Records*

The train operated on multiple test days at a speed under or equal to either 10, 20, or 30 mph (depending on the specific test run). Table 8 is a summary of test conditions.

Table 21. Test Case 2 Train Movements Performed

Test No.	Date	Enter	Exit	Speed (mph)	VB Scale Factor %
1	17-Jun	64	40	10≤	0
2	17-Jun	40	64	10≤	0
3	17-Jun	64	40	20	0
4	17-Jun	40	64	20	0
5	22-Jun	64	40	30	0
6	22-Jun	40	64	30	0
7	23-Jun	64	40	30	0
8	23-Jun	40	64	30	0

6.2.3.2 *Detected Accuracy Record*

The exit accuracy for the system is affected when the device is detecting an outbound movement, noting that VB4 Clear status is related to the physical block (as it is not directly related to the VBTC detection accuracy). The detected accuracy based on each device location is summarized in Table 9, Table 10, and Table 11.

Table 22. Exit Accuracy for R64

Location	R64							Average
Test Run.	Train speed	enters	exits	VB1	VB2	VB3	VB4	
1	10≤	64	40	1711	1684	1622	N/A	1672
3	20	64	40	1680	1739	1686	N/A	1702
5	30	64	40	1948	1869	1872	N/A	1896
7	30	64	40	2202	2326	2239	N/A	2256
Average				1885	1904	1855	N/A	1881

Table 23. Exit Accuracy for R52

Location	R52											Average
Test Run.	Train speed(MPH)	entry	exit	RVB1	RVB2	RVB3	RVB4	LVB1	LVB2	LVB3	LVB4	
1	10≤	R64	R40	N/A	N/A	N/A	N/A	1730	1778	1899	N/A	1803
2	10≤	R40	R64	1304	1122	1113	N/A	N/A	N/A	N/A	N/A	1180
3	20	R64	R40	N/A	N/A	N/A	N/A	1737	2105	1914	N/A	1919
4	20	R40	R64	1600	1518	1434	N/A	N/A	N/A	N/A	N/A	1517
5	30	R64	R40	N/A	N/A	N/A	N/A	1870	1919	1745	N/A	1844
6	30	R40	R64	2338	2126	2243	N/A	N/A	N/A	N/A	N/A	2236
7	30	R64	R40	N/A	N/A	N/A	N/A	1987	2158	1977	N/A	2041
8	30	R40	R64	2380	2202	2332	N/A	N/A	N/A	N/A	N/A	2305
Average				1906	1742	1780	0	1831	1990	1883	N/A	1855

Table 24. Exit Accuracy for R40

Location	R40							Average
Test Run.	Train speed	Enters	Exits	VB1	VB2	VB3	VB4	
2	10≤	40	64	1824	1547	1566	N/A	1646
4	20	40	64	2194	1677	1925	N/A	1932
6	30	40	64	1851	1496	1623	N/A	1657
8	30	40	64	1943	1547	1547	N/A	1679
Average				1953	1567	1665	N/A	1728

6.2.3.3 *Initial Analysis for the Results*

The system detection accuracy in this test is a measurement result between the ideal virtual block boundary and the rear-of-train location at the time the virtual block status changed. Therefore, the result shows the combination of the safety buffer plus the system processing time and the debounce buffer time.

6.3 System Detection Accuracy with Different VB Scale Factor Setting

6.3.1 *Purpose*

Due to operational needs and the varying railroad operation environment, the VBTC system offers the ability to change the VB Scale Factor from 0 to 255 percent. This is done only in areas that have extreme ballast condition changes or widely varying train shunting performance. It should be noted that while increasing the VB Scale Factor will allow more variation in the calibrated transmit current profile, it correspondingly increases the size of the safety buffer, which can decrease the operational efficiency. This test case provides a comparison of the system under different VB Scale Factor settings.

6.3.2 *Test Case Procedures*

This test evaluated the basic constant speed train movement within the test section at various VB Scale Factors. The train consist used in this test had nine rail cars and a single locomotive.

In this test, the VB Scale Factor was set to either 0, 50, 100, or 255 percent (depending on the specific test run). The train with GPS equipment on the locomotive entered the R64 end of the test track section at a selected speed and maintained constant speed movement until exiting at the R52 end of the test section. The same process continued from R52 to R64. Figure 21 shows the two train movements that occurred with each VB Scale Factor.

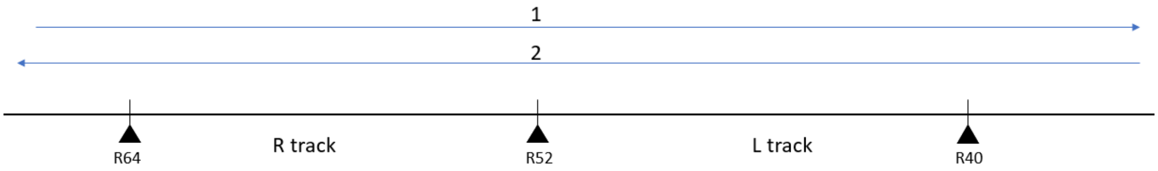


Figure 20. Test Case 3 Train Movement Diagram

The data recorded for this test was obtained from the EC5 device data logs and system logs, and train location was compared with pre-measured ideal virtual block boundary locations and GPS data. The distance from each ideal virtual block boundary to the rear-of train location at the time of change in track status reported by VBTC is considered the system detection accuracy.

6.3.3 *Recorded Test Results*

6.3.3.1 *Test Run Records*

The train was operated on multiple test days with the VB Scale Factor set at either 0, 50, 100, or 255 percent (depending on the specific test run). Table 12 summarizes the train movements.

Table 25. Test Case 3 Test Performed

Test run	Date	Entry	Exit	Speed (mph)	VB Scale Factor %
1	17-Jun	64	40	30	50
2	17-Jun	40	64	30	50
3	17-Jun	64	40	20	100
4	17-Jun	40	64	20	100
5	20-Jun	64	40	30	255
6	20-Jun	40	64	30	255

6.3.3.2 Detected Accuracy Record

The exit accuracy for the system only applies when the device is detecting an outbound train movement and VB4 Clear status is related to the physical block status. The detected accuracy measured for each device location is shown in Table 13.

Table 26. Exit Accuracy Detected for Different VB Scale Factor Settings

	Setting			R64			R52			R40			
Test Run.	**VB factor %**	**entry**	**exit**	**VB1**	**VB2**	**VB3**	**L/R VB1**	**L/R VB2**	**L/R VB3**	**VB1**	**VB2**	**VB3**	**Average**
1	50	64	40	1590	1603	1607	1818	1868	1567	N/A	N/A	N/A	1438
2	50	40	64	N/A	N/A	N/A	1216	1034	1100	2119	1735	1779	
3	100	64	40	1774	1799	1783	2138	1890	1999	N/A	N/A	N/A	1607
4	100	40	64	N/A	N/A	N/A	1442	1319	1310	2157	1676	1723	
5	255	64	40	3011	2712	2856	3245	3150	2845	N/A	N/A	N/A	3197
6	255	40	64	N/A	N/A	N/A	Error	Error	Error	4426	3330	Error	

Note that in Test Run 5, the train exited the physical block before VB3 showed Clear; the location for VB3 Clear is not reliable as the physical block was no longer occupied. In Test Run 6, when the train was within the R52-R64 physical block, the R52 VBTC device showed that VBTC mode was still active, but no Clear status for any virtual block was shown until the train exited the physical block. Table 14 provides the data log record.

Table 27. R52 Data Log Record, R52 to R64

Location	R52	**Begin**	R40	**Note**	TCR run, 30 mph, VBF=255, back and forth					
Train speed	30 MPH	**End**	R64							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
1	Train enters the L block	16:13:34								
2	LVB4 occupied	16:13:36								F
3	LVB3 occupied	16:14:57							F	
4	LVB2 occupied	16:16:04						F		
5	LVB1 occupied	16:17:12					F			
6	Train enters the R block	16:18:04								
7	RVB1-4 occupied	16:18:04	F	F	F	F				
8	Train exits the L block	16:18:14								
9	LVB1-3 clear	16:18:17					T	T	T	
10	LVB4 clear	16:18:22								T
11	Train exits the R block	16:22:43								
12	RVB1-3 clear	16:22:46	T	T	T					
13	RVB4 clear	16:22:51				T				

6.3.3.3 Initial Analysis of Test Results

The VB Scale Factor can be set up to 255 percent; however, some detection issues were observed in which a block was not cleared with the train movement and some detection results were longer than a virtual block length.

6.4 Changing Speed Test

6.4.1 Purpose

This test evaluated significant changes in train speed after the system was fully calibrated, which was necessary to determine how sensitive the calibration process is to train speed variations.

This test focused on an accelerating train scenario, while some other test cases used as comparison involved decelerating scenarios.

6.4.2 Test Case Procedures

The train consist comprised nine rail cars and a single locomotive, which performed an accelerating train movement within the test track section. The VB Scale Factor was set to 0 percent.

In this test, as shown in Figure 22, the train entered at R64 at a speed of 10 mph, increasing the speed during the test section, and exited at R52 at a speed of 45 mph. During the second round, the train entered at R52 at a speed of 10 mph, increasing the speed while in the test section, and exited from R64 at 35 mph.

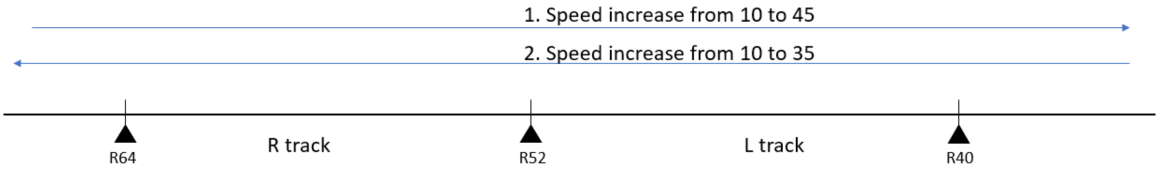


Figure 21. Test Case 4 Train Movement Diagram

The data recorded for this test was obtained from the EC5 device data logs and system logs.

6.4.3 Recorded Test Results

Results are provided by device location, train movement, and corresponding VB status in Table 15 through Table 20.

Table 28. R64 Data Log Record, R64 to R40

Location	R64	**Begin**	R64	Note	Changing speed 10~45 mph. VBF=0	
Train speed	0-45 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	16:59:02				
2	VB1-4 occupied	16:59:02	F	F	F	F
3	VB1 clear	17:01:49	T			
4	VB2 clear	17:02:41		T		
5	VB3 clear	17:03:41			T	
6	Train exits the block	17:03:56				
7	VB4 clear	17:04:04				T

Table 29. R64 Data Log Record, R40 to R64

Location	R64	**Begin**	R40	Note	Changing speed 10~35 mph. VBF=0	
Train speed	0-35 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	17:24:38				
2	VB4 occupied	17:24:41	F			
3	VB3 occupied	17:25:50		F		
4	VB2 occupied	17:26:47			F	
5	VB1 occupied	17:27:44				F
6	Train exits the block	17:28:37				
7	VB1-3 clear	17:28:41	T	T	T	
8	VB4 clear	17:28:45				T

Table 30. R52 Data Log Record, R64 to R40

Location	R52	**Begin**	R64	Note						
Train speed	0-45 MPH	**End**	R40		Changing speed 10-45 MPH. VBF=0					
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the R block	15:56:30								
2	RVB4 occupied	15:56:33				F				
3	RVB3 occupied	15:57:44			F					
4	RVB2 occupied	15:58:54		F						
5	RVB1 occupied	15:59:54	F							
6	Train enters the L block	16:00:57								
7	LVB1-4 occupied	16:00:57					F	F	F	F
8	Train exits the R block	16:01:09								
9	RVB1-3 clear	16:01:12	T	T	T					
10	RVB4 clear	16:01:16				T				
11	LVB1 clear	16:03:29					T			
12	LVB2 clear	16:04:34						T		
13	LVB3 clear	16:05:36							T	
14	Train exits the L block	16:05:40								
15	LVB4 clear	16:05:47								T

Table 31. R52 Data Log Record, R40 to R64

Location	R52	**Begin**	R40	Note						
Train speed	0-35 MPH	**End**	R64		Changing speed 10-35 MPH. VBF=0					
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the L block	17:19:23								
2	LVB4 occupied	17:19:26								F
3	LVB3 occupied	17:21:50							F	
4	LVB2 occupied	17:22:58						F		
5	LVB1 occupied	17:23:59					F			
6	Train enters the R block	17:24:39								
7	RVB1-4 occupied	17:24:40	F	F	F	F				
8	Train exits the L block	17:24:48					T	T	T	
9	LVB1-3 clear	17:24:49								T
10	LVB4 clear	17:24:56								
11	System exits VBTC mode R	17:26:45								
12	Train exits the R block	17:28:39	T	T	T	T				
13	System return to VBTC mode R	17:28:46								

Table 32. R40 Data Log Record, R64 to R40

Location	R40	**Begin**	R64	Note	Changing speed 10-45 mph. VBF=0	
Train speed	0-45 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	17:03:48				
2	System exit the VBTC mode	17:03:59	F	F	F	F
3	Train exits the block	17:07:25				
4	System returns to VBTC mode	17:07:32	T	T	T	T

Table 33. R40 Data Log Record, R40 to R64

Location	R40	**Begin**	R40	Note	Changing speed 10-35 mph. VBF=0	
Train speed	0-35 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	17:19:25				
2	VB1-4 occupied	17:19:25	F	F	F	F
3	VB1 clear	17:22:23	T			
4	VB2 clear	17:23:20		T		
5	VB3 clear	17:24:18			T	
6	Train exits the block	17:24:47				
7	VB4 clear	17:24:54				T

6.4.4 Initial Test Results Analysis

In the R64 to R52 test run, the R40 device, as the inbound side for the movement between R52 to R40, exited VBTC mode. The system log recorded the exit reason as:

Location Disabled - Far Entry Threshold Not Met

The reason for this VBTC mode failure, according to the manual, is that the far side (R52L in this scenario) threshold check failed shortly after the train entered the block. If this check continues to fail, the manual's suggested mitigation is to adjust the VB Scale Factor.

During the R52 to R64 test run, the R52 R track side, as the outbound side for the movement between R52 to R64, exited VBTC mode. The system log recorded the exit reason as:

Location Disabled - Bad Signal Quality

According to the manual, the reason for this VBTC mode failure is "Signal Quality fault detected (due to rapid decrease in TX current) for an Outbound train," and the system log recorded the pulses as:

pulses 3181 3309 3370 3428 3444 3459 3443 3459 (newest to oldest)

Figure 23 shows the analog data record for whole train movement for the R52 R track (between R64 to R52) side.

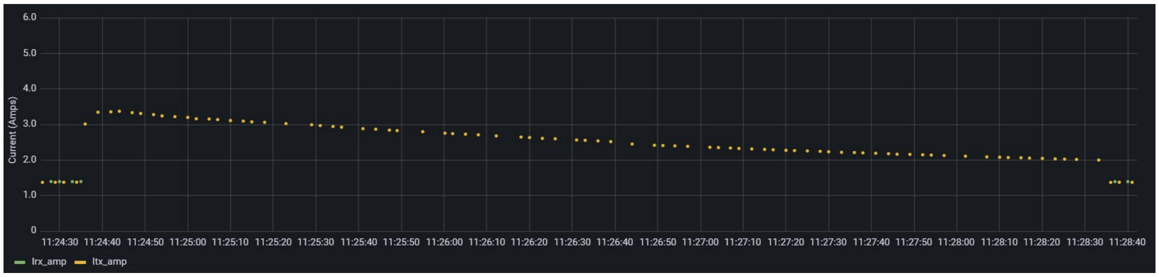


Figure 22. Test Case 4 TxC and RxC Record

6.5 Single Locomotive Test

6.5.1 Purpose

This test evaluated the system performance under extreme operation conditions. Testing with done with a single locomotive without cars, as this is the worst shunting rail condition aside from that of a hi-rail vehicle, which is normally protected by a work authority (bidirectional authority).

6.5.2 Test Case Procedures

The train consist comprised a single locomotive without cars, which performed a constant speed train movement within the test section.

In this test, as shown in Figure 24, the locomotive entered at R64 at a speed of 20 mph and maintained constant speed until it exited the two blocks. Then, the locomotive reversed and entered at R40 at a speed of 20 mph and maintained constant speed until exiting the block from R64. The test was repeated with the same conditions.

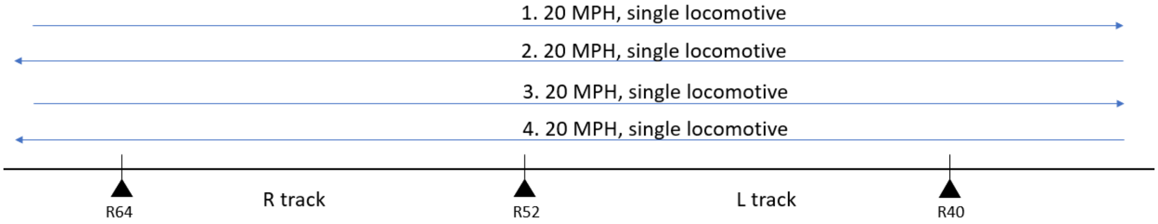


Figure 23. Test Case 5 Train Movement

In this test, the physical block “Unshunt” status was triggered and recorded by the system log while the locomotive was still within the related physical block, so it was considered a loss of shunt (LOS) event.

6.5.3 Recorded Test Results

Results are provided by device location, train movement, and corresponding VB status in Table 21 through Table 22.

Table 34. R64 Data Log Record, R64 to R40 Run 1

Location	R64	**Begin**	R64	Note	Single locomotive, 20 mph, VBF=0%	
Train speed	20 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	18:58:51				
2	VB1-4 occupied	18:58:51	F	F	F	F
3	VB1 clear	19:01:33	T			
4	VB2 clear	19:03:09		T		
5	VB3 clear	19:04:22			T	
6	LOS detected	19:04:50				
7	LOS detected	19:05:01				
8	System exit VBTC mode	19:05:01	F	F	F	
9	Train exits the block	19:05:27				
10	System returns to VBTC mode	19:05:34	T	T	T	T

Table 35. R64 Data Log Record, R40 to R64 Run 2

Location	R64	**Begin**	R40	Note	Single locomotive, 20 mph, VBF=0%	
Train speed	20 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:23:00				
2	VB4 occupied	19:23:06	F			
3	LOS detected	19:23:32				
4	VB3 occupied	19:25:04		F		
5	VB2 occupied	19:26:42			F	
6	VB1 occupied	19:28:19				F
7	Train exits the block	19:29:37				
8	VB1-3 clear	19:29:37	T	T	T	
9	VB4 clear	19:29:44				T

Table 36. R64 Data Log Record, R64 to R40 Run 3

Location	R64	**Begin**	R64	Note	Single locomotive, 20 mph, VBF=0	
Train speed	20 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:34:01				
2	VB1-4 occupied	19:34:01	F	F	F	F
3	VB1 clear	19:36:46	T			
4	VB2 clear	19:38:19		T		
5	VB3 clear	19:39:37			T	
6	LOS detected	19:40:05				
7	System exit VBTC mode	19:40:15	F	F	F	
8	Train exits the block	19:40:38				
9	System returns to VBTC mode	19:40:46	T	T	T	T

Table 37. R64 Data Log Record, R64 to R40 Run 4

Location	R64	**Begin**	R40	Note	Single locomotive, 20 mph, VBF=0	
Train speed	20 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	20:03:07				
2	VB4 occupied	20:03:15	F			
3	LOS detected	20:03:41				
4	LOS detected	20:03:46				
5	VB3 occupied	20:05:16		F		
6	LOS detected	20:06:24				
7	VB2 occupied	20:06:54			F	
8	VB1 occupied	20:08:30				F
9	Train exits the block	20:09:43				
10	VB1-3 clear	20:09:46	T	T	T	
11	VB4 clear	20:09:51				T

Table 38. R52 Data Log Record, R64 to R40 Run 1

Location	R52	**Begin**	R64	Note						
Train speed	20 MPH	**End**	R40		Single locomotive, 20 mph, VBF=0					
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enterss the R block	18:58:49								
2	RVB4 occupied	18:58:52	F							
3	RVB3 occupied	19:00:56		F						
4	RVB3 clear	19:02:06		T						
5	RVB3 occupied	19:02:11		F						
6	RVB2 occupied	19:02:06			F					
7	RVB1 occupied	19:04:14				F				
8	RVB1 clear	19:04:27				T				
9	LOS detected	19:04:41								
10	LOS detected	19:04:49								
11	RVB2 clear	19:04:52			T					
12	LOS detected	19:04:59								
13	RVB1-2 occupied	19:05:05			F	F				
14	Train enterss the L block	19:05:24								
15	LVB1-4 occupied	19:05:24					F	F	F	F
16	Train exitss the R block	19:05:26								
17	RVB1 clear	19:05:27	T							
18	RVB2-3 clear	19:05:29		T	T					
19	RVB4 clear	19:05:33				T				
20	System exitss VBTC mode L	19:05:53								
21	Train exitss the L block	19:12:06								
22	System return to VBTC mode L	19:12:14					T	T	T	T

Table 39. R52 Data Log Record, R40 to R64 Run 2

Location	R52	**Begin**	R40	Note						
Train speed	20 MPH	**End**	R64		Single locomotive, 20 mph, VBF=0					
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the L block	19:16:20								
2	LVB4 occupied	19:16:23								F
3	LVB3 occupied	19:18:28							F	
4	LVB2 occupied	19:20:09						F		
5	LVB1 occupied	19:22:30					F			
6	Train enters the R block	19:22:59								
7	Train exits the L block	19:23:01								
8	LVB1-3 clear	19:23:02					T	T	T	
9	RVB1-4 occupied	19:23:07	F	F	F	F				
10	LVB4 clear	19:23:09								T
11	LOS detected	19:23:33	T	T						
12	RVB1-2 clear	19:23:34			T	T				
13	RVB3-4 clear	19:23:41								
14	System exits the VBTC mode R	19:23:43	F	F	F	F				
15	Train exits the R block	19:29:36								
16	System return to VBTC mode R	19:29:43	T	T	T	T				

Table 40. R52 Data Log Record, R64 to R40 Run 3

Location	R52	**Begin**	R64	Note	Single locomotive, 20 mph, VBF=0					
Train speed	20 MPH	**End**	R40							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enterss the R block	19:34:02								
2	RVB4 occupied	19:34:02				F				
3	RVB3 occupied	19:36:10			F					
4	RVB2 occupied	19:37:49		F						
5	LOS detected	19:40:04								
6	RVB2 clear	19:40:07		T						
7	RVB3-4 clear	19:40:12			T	T				
8	System exitss VBTC mode R	19:40:14	F	F	F	F				
9	Train enterss the L block	19:40:37								
10	Train exitss the R block	19:40:37								
11	System returns to VBTC mode R	19:40:45	T	T	T	T				
12	System exitss the VBTC mode L	19:40:49					F	F	F	F
13	Train exitss the L block	19:47:16								
14	System returns to VBTC mode L	19:47:23					T	T	T	T

Table 41. R52 Data Log Record, R40 to R64 Run 4

Location	R52	**Begin**	R40	Note	Single locomotive, 20 mph, VBF=0					
Train speed	20 MPH	**End**	R64							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the L block	19:56:32								
2	LVB4 occupied	19:56:32								F
3	LVB3 occupied	19:58:41							F	
4	LVB2 occupied	20:00:19						F		
5	LVB1 occupied	20:02:39					F			
6	Train enters the R block	20:03:09								
7	Train exits the L block	20:03:10								
8	LVB1-3 clear	20:03:11					T	T	T	
9	RVB1-4 occupied	20:03:11	F	F	F	F				
10	LVB4 clear	20:03:18	T							T
11	RVB1 clear	20:03:38								
12	LOS detected	20:03:40								
13	RVB2-4 clear	20:03:47		T	T	T				
14	System exits the VBTC mode R	20:03:50	F	F	F	F				
15	Train exits the R block	20:09:44								
16	System return to VBTC mode	20:09:52	T	T	T	T				

Table 42. R40 Data Log Record, R64 to R40 Run 1

Location	R40	**Begin**	R64	Note	Single locomotive, 20 mph, VBF=0	
Train speed	20 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:05:25				
2	VB4 occupied	19:05:25				F
3	VB3 occupied	19:07:55			F	
4	VB2 occupied	19:09:26		F		
5	VB1 occupied	19:10:51	F			
6	Train exits the block	19:12:05				
7	VB1-VB3 clear	19:12:09	T	T	T	
8	VB4 clear	19:12:13				T

Table 43. R40 Data Log Record, R40 to R64 Run 2

Location	R40	**Begin**	R40	Note	Single locomotive, 20 mph, VBF=0	
Train speed	20 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:16:22				
2	VB1-4 occupied	19:16:22	F	F	F	F
3	VB1 clear	19:18:58	T			
4	VB2 clear	19:20:24		T		
5	VB3 clear	19:21:24			T	
6	Train exits the block	19:23:00				
7	VB4 clear	19:23:07				T

Table 44. R40 Data Log Record, R64 to R40 Run 3

Location	R40	**Begin**	R64	Note	Single locomotive, 20 mph, VBF=0	
Train speed	20 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:40:38				
2	VB4 occupied	19:40:38				F
3	VB3 occupied	19:43:10			F	
4	VB2 occupied	19:44:39		F		
5	VB1 occupied	19:46:05	F			
6	Train exits the block	19:47:17				
7	VB1-VB3 clear	19:47:21	T	T	T	
8	VB4 clear	19:47:25				T

Table 45. R40 Data Log Record, R40 to R64 Run 4

Location	R40	**Begin**	R40	Note	Single locomotive, 20 mph, VBF=0	
Train speed	20 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:56:30				
2	VB1-4 occupied	19:56:30	F	F	F	F
3	VB1 clear	19:59:08	T			
4	VB2 clear	20:00:28		T		
5	System exit the VBTC mode	20:00:40	F	F		
6	Train exits the block	20:03:09				
7	System returns to VBTC mode	20:03:16	T	T	T	T

6.5.4 Initial Analysis

Based on the system log, several events related to the system exiting VBTC mode were recorded with reasons as follows:

R64: Run 1- Virtual Blocks Disabled - Invalid Following Train

Run 3- Virtual Blocks Disabled - Invalid Following Train

R52: Run 1- Location Disabled - Bad Signal Quality

Run 2- Location Disabled - TxC Too High When Not Shunted

Run 3- Location Disabled - TxC Too High When Not Shunted

Run 3- Location Disabled - Near Entry Threshold Not Met

Run 4- Location Disabled - TxC Too High When Not Shunted

R40: Run 4- Location Disabled - Bad Signal Quality

According to the manual, invalid following train status is triggered during an outbound movement when the system detects a high-speed reverse movement. The "TxC too high when not shunted" status is triggered when the TxC amplitude is greater than the Far Entry Threshold Maximum when VB Unshunt status is True for longer than 9.8 seconds. "Near Entry Threshold Not Met" indicates that the "One of the five pulses need to be within the near TxC Threshold limits" criterion is not met.

The currents measured at R52 for four train runs are shown in Figure 25 and Figure 26.

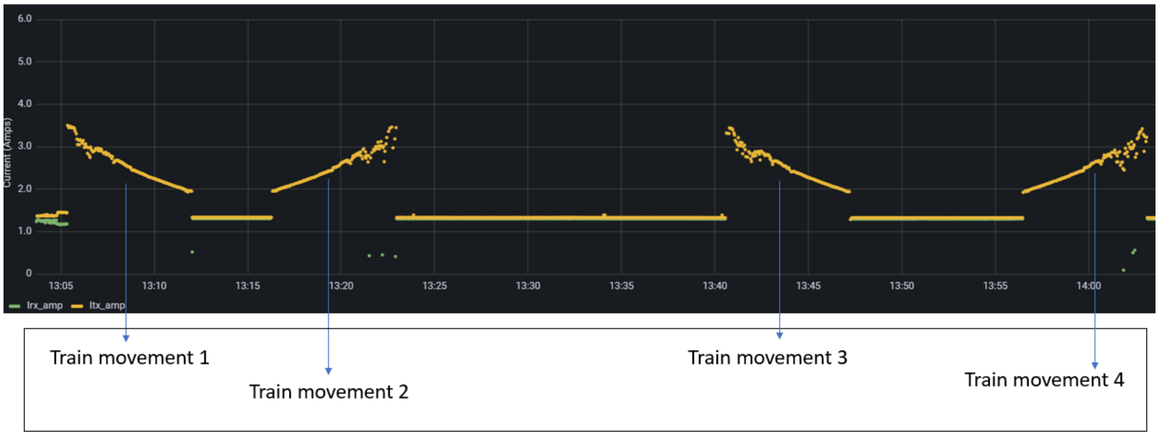


Figure 24. Test Case 5 TxC and RxC Record (R52, R52-R40 section)

Figure 25. Test Case 5 TxC and RxC Record (R52, R64-R52 section)

6.6 Pull-Apart Test

6.6.1 *Purpose*

In actual operating scenarios, train pull-aparts can create an operational hazard, so a pull-apart scenario was simulated in the test environment.

6.6.2 *Test Case Procedures*

In this test, the train consist comprised nine railcars and a single locomotive and the VB Scale Factor was set to 0 percent.

The train, as shown in Figure 27, entered at R64 at a speed of 20 mph, and stopped at R59. The train consist was then disconnected in the middle and five railcars were left occupying the block, while the locomotive was towed out of the test section along with the first four railcars.

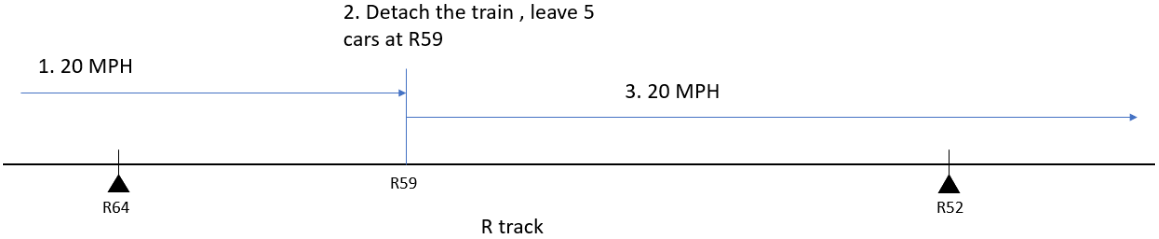


Figure 26. Test Case 6 Train Movement Diagram

Since there were five rail cars left near the R59 section, the physical block would not indicate Clear after the leading section of the train exited the block.

The data recorded for this test was obtained from the EC5 device data log and system log.

6.6.3 *Recorded Test Results and Initial Analysis*

Table 33 and Table 34 provide results by device location, train movement, and corresponding VB status.

Table 46. R64 Data Log Record, R64 to R52

Location	R64	**Begin**	R64	Note		
Train speed	20 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:54:35				
2	VB1-4 occupied	19:54:36	F	F	F	F

Table 47. R52 Data Log Record, R64 to R52

Location	R52	**Begin**	R64	Note							
Train speed	20 MPH	**End**	R52								
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**	
0	Initial Status	N/A	T	T	T	T	T	T	T	T	
1	Train enters the R block	19:54:36									
2	RVB4 occupied	19:54:36	F								
3	RVB3 occupied	19:56:30		F							
4	RVB2 occupied	20:02:23			F						
5	RVB1 occupied	20:05:15				F					
6	Train enters the L block	20:08:23									
7	LVB1-4 occupied	20:08:23					F	F	F	F	
8	RVB1 clear	20:08:38	T								
9	RVB2 clear	20:08:41		T							

As indicated by the data log, the system can offer protection against a pull-apart in the same way as a conventional physical block, since the virtual block in which the detached train section was located still showed occupancy, even after the leading train section cleared the block.

6.7 Double Occupancy within Single Block Test

6.7.1 Purpose

Since VBTC detection equipment only connects to the ends of a physical block, VBTC cannot detect a rail break or occupancy in the track section between two shunting items within the same physical block. The VBTC system will show all the virtual block sections between two shunts as occupied. A test case was needed to simulate this scenario.

6.7.2 Test Case Procedures

In this test, as shown in Figure 28, a five-car train without a locomotive was located stationary at R59. A train consist with four railcars and a single locomotive entered the physical block at R52 at a speed of 20 mph, stopped at R59, coupled to the five stationary cars, and then the entire train consist exited at R64 at a speed of 20 mph.

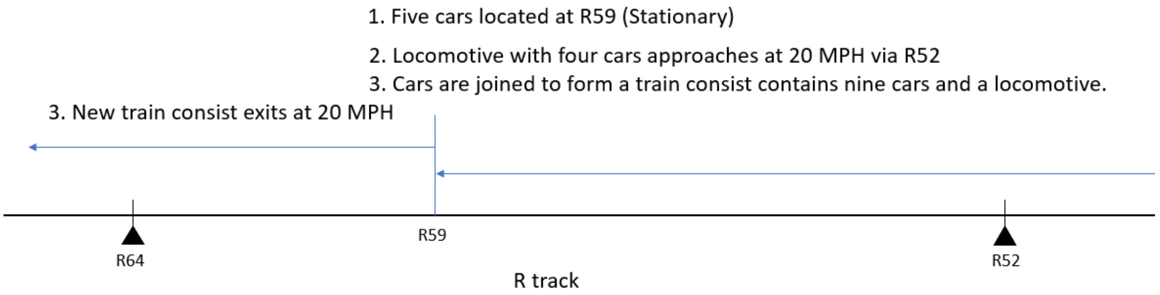


Figure 27. Test Case 7 Train Movement

The data recorded for this test was obtained from the EC5 device data log and system log.

6.7.3 Recorded Test Results

Results are provided by device location, train movement, and corresponding VB status in Table 35 and Table 36.

Table 48. R40 Data Log Record, R52 to R64

Location	R64	**Begin**	R52	Note		
Train speed	20 mph	**End**	R64			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	F	F	F	F
1	Train exits the block	20:45:22				
2	VB1-3 clear	20:45:23	T	T	T	
3	VB4 clear	20:45:29				T

Table 49. R52 Data Log Record, R52 to R64

Location	R52	**Begin**	R52	Note						
Train speed	20 MPH	**End**	R64							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	F	F	F	F	F	F
1	RVB2 occupied	20:15:43	F							
2	RVB1 occupied	20:15:45		F						
3	Train exits the L block	20:15:50								
4	LVB1-3 clear	20:15:51					T	T	T	
5	LVB4 clear	20:15:57								T
6	RVB1 clear	20:18:06	T							
7	RVB2 clear	20:33:27		T						
8	RVB3 clear	20:43:30			T					
9	Train exits the R block	20:45:19								
10	RVB4 clear	20:45:27				T				

6.7.4 *Initial Analysis*

When the train entered the block at the R52 section, the movement direction from R52 was from RVB1 to RVB4. The ideal occupied status should be that RVB1 and RVB2 are occupied at the same time.

In the data log record, the occupancy status shows RVB2 was occupied first and then RVB1 was occupied a few seconds later. This is likely due to the total shunting resistance from the train decreasing after more axles entered the block, causing a rise in TxC current that can appear similar to a train inbound movement. After the train fully entered the block, TxC decreased with further train movement in the same direction.

This short-time rising approach of TxC current was recorded by the system between 14:15 to 14:16 (Figure 29).

Dot in rising approach

Figure 28. Test Case 7 TxC and RxC Record (R52, R64-R52 section)

6.8 Changing Movement Direction within Single Block

6.8.1 Purpose

In a railroad operating environment, there are multiple scenarios that require a train to change the direction of movement. A test scenario was set up to simulate a changing direction operation.

6.8.2 Test Case Procedures

In this test, as shown in Figure 30, a train consist comprising four railcars and a single locomotive entered at R64 at a speed of 20 mph, fully stopped with the front of the train at R55, performed a reverse movement to R59, stopped, and then performed a forward move at a speed of 20 mph and exited the block from R52. The VB Scale Factor was set to 0 percent,

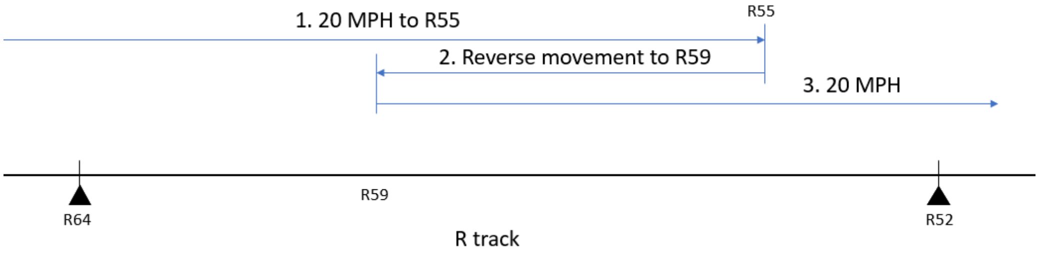


Figure 29. Test Case 8 Train Movement Diagram

The data recorded for this test was obtained from the EC5 device data log and system log.

6.8.3 Recorded Test Results and Initial Analysis

Table 37 and Table 38 provide test results by device location, train movement, and corresponding VB status.

Table 50. R64 Data Log Record, R64 to R52

Location	R64	**Begin**	R64	Note		
Train speed	20 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	21:00:06				
2	VB1-4 occupied	21:00:06	F	F	F	F
3	VB1 clear	21:03:06	T			
4	VB2 clear	21:04:46		T		
5	VB2 occupied	21:07:17		F		
6	VB2 clear	21:12:57		T		
7	VB3 clear	21:14:33			T	
8	Train exits the block	21:15:03				
9	VB4 clear	21:15:11				T

Table 51. R52 Data Log Record, R64 to R52

Location	R52	Begin	R64	Note						
Train speed	20 MPH	End	R52							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the R block	21:00:05								
2	RVB4 occupied	21:00:08	F							
3	RVB3 occupied	21:02:03		F						
4	RVB2 occupied	21:03:42			F					
5	RVB1 occupied	21:05:10				F				
6	RVB1 clear	21:07:12	T							
7	RVB1 occupied	21:13:23	F							
8	Train enters the L block	21:14:56								
9	LVB1-4 occupied	21:14:56					F	F	F	F
10	Train exits the R block	21:15:02								
11	RVB1-3 clear	21:15:05	T	T	T					
12	RVB4 clear	21:15:09				T				

As can be observed from the record, the system operated as expected, detecting the reverse train movement within a single physical block.

6.9 Broken Rail Test with Multiple Scenarios

6.9.1 *Purpose*

As a feature of the EC5 VBTC system running in the VBTC mode, a broken rail can be detected when the physical block is occupied, and the broken rail location can be reported as non-vital information. Two test scenarios were set up to verify this feature.

6.9.2 *Test Case Procedures*

In this test, the train consist comprised 9 rail cars and a single locomotive, the VB Scale Factor was set to 0 percent, and the broken rail trap was set up at the R46 IJ location and triggered based on the test needs. Two train movements were performed during this test, as shown in Figure 31, Figure 32, and Figure 33.

In the first test, the train entered at R52 at a speed of 20 mph and maintained constant speed movement until the train exited at R40. When the train was overlapping the R46 IJ, the broken rail (BR) was triggered at the R46 IJ location. When the train was located at R43, the BR was recovered then recreated before the train fully exited the block.

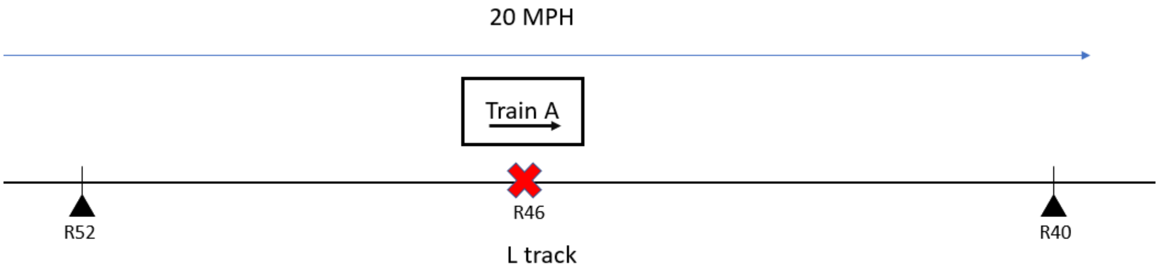


Figure 30. First Broken Rail and Train Location

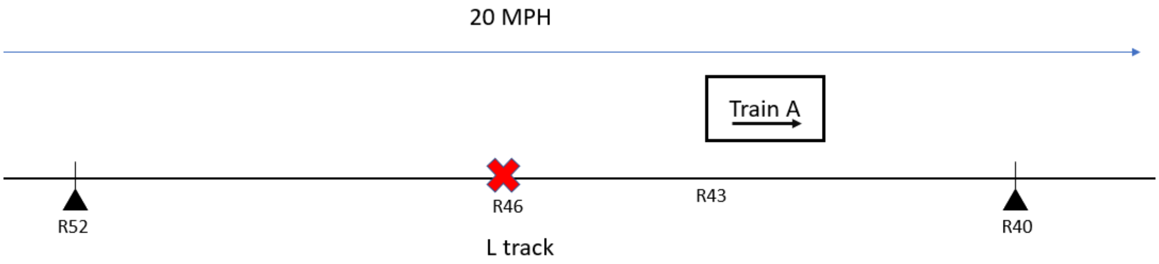


Figure 31. Second Broken Rail and Train Location

In the second test, the train entered at R40 at a speed of 20 mph and maintained constant speed movement until the train exited at R64. When the train was located at R51, the BR was triggered at the R46 IJ location. This test was used to simulate a spontaneous rail break which occurs away from the train location.

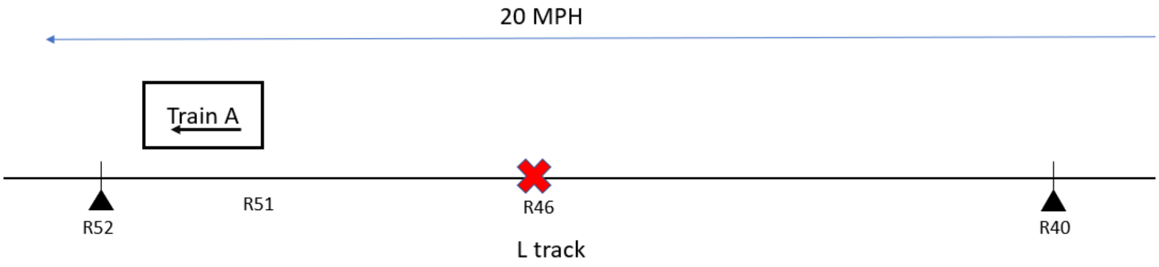


Figure 32. First Broken Rail and Train Location

The data recorded for this test was obtained from the ElectroLogIXS/EC5 device data log and system log.

6.9.3 Recorded Test Results

Results are provided by device location, train movement, and corresponding VB status in Table 39 through Table 42.

Table 52. R40 Data Log Record, R52 to R40

Location	R40	**Begin**	R52	Note		
Train speed	20 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	20:45:34				
2	VB4 occupied	20:45:37	F			
3	VB3 occupied	20:48:04		F		
4	VB2 occupied	20:49:41			F	
5	VB1 occupied	20:51:08				F
6	BR detected	20:52:36				
7	System exit the VBTC mode	20:52:36				
8	BR recovered	20:54:27				
9	System returns to VBTC mode	20:54:34				

Table 53. R40 Data Log Record, R40 to R52

Location	R40	**Begin**	R40	Note		
Train speed	20 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	21:01:22				
2	VB1-4 occupied	21:01:25	F	F	F	F
3	VB1 clear	21:04:06	T			
4	VB2 clear	21:05:34		T		
5	VB3 clear	21:07:16			T	
6	BR detected, location reported	21:07:35				
7	System exit the VBTC mode	21:07:35	F	F	F	
8	BR recovered	21:12:00				
9	System returns to VBTC mode	21:12:08	T	T	T	T

Table 54. R52 Data Log Record, R52 to R40

Location	R52	**Begin**	R52	Note						
Train speed	20 MPH	**End**	R40							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A					T	T	T	T
1	Train enters the L block	20:45:35								
2	LVB 1-4 occupied	20:45:35					F	F	F	F
3	LVB 1 clear	20:48:28					T			
4	BR detected, location reported	20:49:21								
5	System exits the VBTC mode L	20:49:21					F			
6	BR recovered	20:49:55								
7	BR detected, no location report	20:50:16								
8	BR recovered	20:54:28								
9	System returns to VBTC mode	20:54:36					T	T	T	T

Table 55. R52 Data Log Record, R40 to R52

Location	R52	**Begin**	R40	Note						
Train speed	20 MPH	**End**	R52							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A					T	T	T	T
1	Train enters the L block	21:01:21								
2	LVB4 occupied	21:01:23					F			
3	LVB3 occupied	21:03:37						F		
4	LVB2 occupied	21:05:13							F	
5	LVB1 occupied	21:06:51								F
6	Train enters the R block	21:07:59								
7	RVB 1-4 occupied	21:08:02								
8	BR detected	21:08:22								
9	System exits the VBTC mode L	21:08:22								
10	BR recovered	21:12:01								
11	System returns to VBTC mode L	21:12:09					T	T	T	T

6.9.4 Initial Analysis

For the R52 to R40 train movement, R52 served as the outbound side. During this movement, two broken rail events were created and detected. The detailed information offered by the system was as follows:

1. The system exited VBTC mode after it detected the rail break and had the following location report: "Slot 1 Track 1 (LTK_VB) Track Integrity Lost at 54.4 (6,473 feet);" this location shows the BR at R46.

2. After reconnecting the BR section while the train was still within the block, the system did not resume VBTC mode and the second BR was recorded without the location report.

For the R40 to R52 train movement, R40 served as the outbound side. During this movement, one broken rail event was created and detected. The detailed information offered by the system was as follows:

The system exited the VBTC mode after it detected a rail break and provided the following location report: “Slot 1 Track 1 (LTKO1) Track Integrity Lost at 95.4 (11,352 feet).” This indicates the BR based on the EOT location of R51, while the actual BR location was at R46. This illustrates why the *location* of a rail break reported by VBTC cannot be used for vital purposes, since it is based on the EOT location at the time a break is detected even if the break occurred spontaneously further behind the train.

6.10 Power Outage Test

6.10.1 Purpose

In this test, two power outage scenarios were simulated, one where the train remains at the same location during the power outage, and the second where the train enters the block while the power is off and continues moving within the block when power is resumed.

6.10.2 Test Case Procedures

In this test, the train consist comprised nine railcars and a single locomotive and the VB Scale Factor was set to 0 percent. Two different scenarios were tested.

Scenario 1: The train, as shown in Figure 34, entered at R64 and stopped at R57, at which time the power for the R52 bungalow was turned off. The train remained at the same location when power was resumed and, after a certain time, the train resumed movement and exited the block.

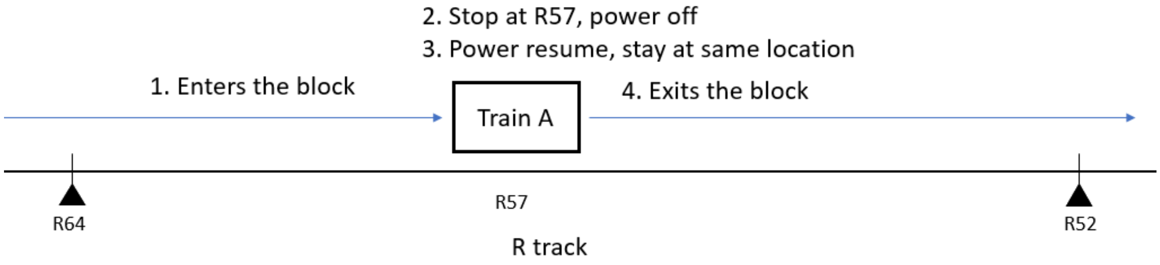


Figure 33. Test Case 10 Train Movement Diagram Scenario 1

Scenario 2: The train, as shown in Figure 35, was outside of the R52-R64 block at the R52 side when power was turned off, entered the block during the power outage, was still moving within the block when power was restored, and then exited the block.

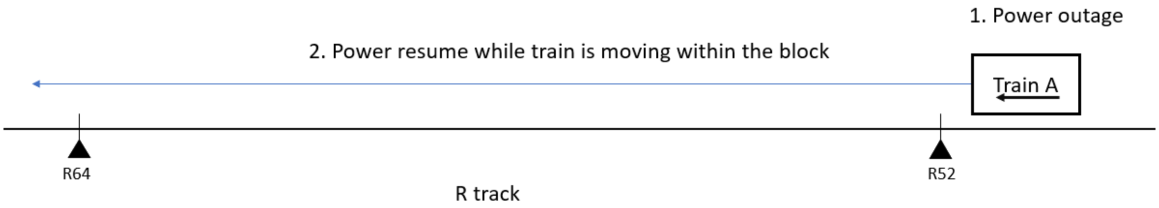


Figure 34. Test Case 10 Train Movement Diagram Scenario 2

The data recorded for this test was obtained from the ElectoLogIXS/EC5 device data log and system log.

6.10.3 Recorded Test Results and Initial Analysis

Table 43 and Table 44 provide results by device location, train movement, and corresponding VB status.

Table 56. R52 Data Log Record, R64 to R52

Location	R52	**Begin**	R64	Note						
Train speed	0 MPH	**End**	R52							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T				
1	Train enters the R block	21:38:16								
2	RVB4 occupied	21:38:16	F							
3	RVB3 occupied	21:39:58		F						
4	Power outage									
5	Power resume	21:42:31								
6	System check, VBTC mode not active L/R	21:42:43	F	F	F	F				
7	System returns to VBTC mode L	21:42:59								
8	Train exits the R block	21:47:28								
9	System returns to VBTC mode R	21:47:36	T	T	T	T				

Table 57. R52 Data Log Record, R52 to R64

Location	R52	**Begin**	R52	Note						
Train speed	20 MPH	**End**	R64							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T				
1	Power outage									
2	Power resume	21:55:43								
3	System check, VBTC mode not active L/R	21:55:55	F	F	F	F				
4	System returns to VBTC mode L	21:56:09								
5	Train exits the R block	21:57:25								
6	System returns to VBTC mode R	21:57:33	T	T	T	T				

As observed from the data log and system log, when the power was reset and the physical track was occupied during the initial system check, the system did not activate VBTC mode for that physical block until the physical block was cleared.

6.11 Loss of Shunt Test

6.11.1 Purpose

Since the VBTC system divides the conventional physical block into multiple, smaller virtual blocks, loss of shunt and the associated false Clear risk is different from a conventional physical block. A more detailed analysis of this can be found in Section 9 of the VBTC Concept of Operations document provided in Appendix A of this report.

6.11.2 Test Case Procedures

In this test, the train consist comprised nine railcars and a single locomotive and the VB Scale Factor was set to 0 percent. Three different scenarios were tested. The first scenario simulated a rusty surface observed by the inbound direction VBTC device, as shown in Figure 36. In this case, the train entered at the R64 section at a speed of 20 mph, stopped at the R59 location, and then a shunt was created at the R57 location. The train resumed forward movement after a certain amount of time and exited at R52 at the speed of 20 mph.

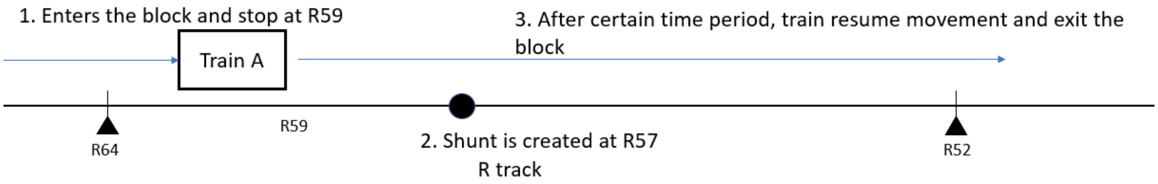


Figure 35. Test Case 11 Train Movement Diagram Scenario 1

This test case simulated the scenario shown in Figure 37.

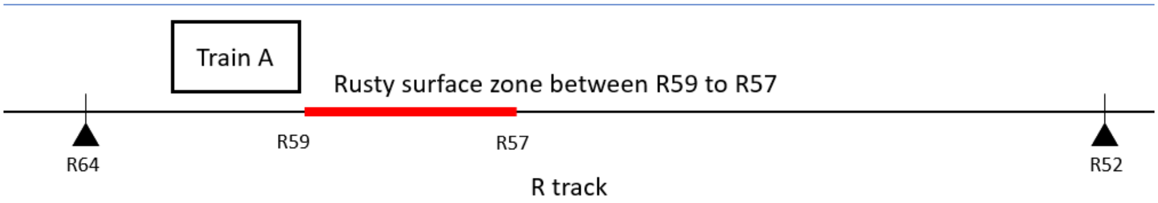


Figure 36. Test Case 11 Simulated Scenario 1

In the scenario shown in Figure 37, a rusty surface was simulated between R59 and R57 so that from the R52 VBTC device, when the train entered the simulated rusty zone, the shunting location remained at R59 until the train exited the rusty zone at R57.

The second scenario, as shown in Figure 38, simulated a rusty surface observed from the outbound direction VBTC device, with the rusty surface length of approximately 2,500 feet (the train length was approximately 503 feet). The train entered at the R64 section at a speed of 20 mph, stopped at the R61 location, and then the shunt was created at the R59 location. The train then resumed forward movement and stopped at R56, the shunt was removed after a certain amount of time, and the train resumed forward movement and exited at R52 at the speed of 20 mph.

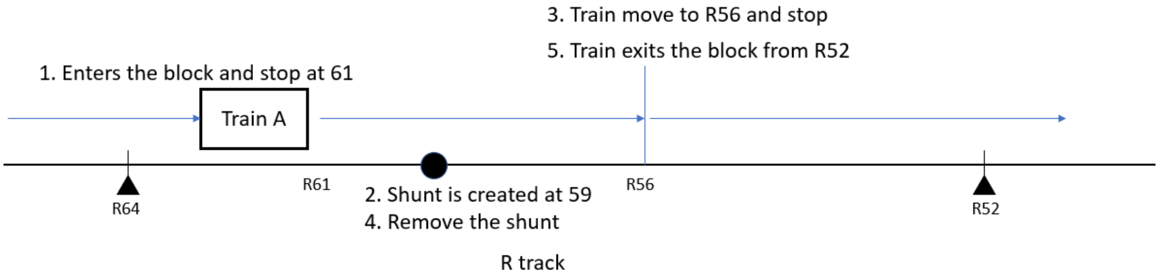


Figure 37. Test Case 11 Train Movement Diagram Scenario 2

In the second scenario, as shown in Figure 39, a rusty surface was simulated between R59 and R57, so that from the R64 VBTC device, when the end of the train entered the simulated rusty zone, the shunting location would suddenly move from R59 to R56.5. Removing the shunt simulated this sudden shunt location change.

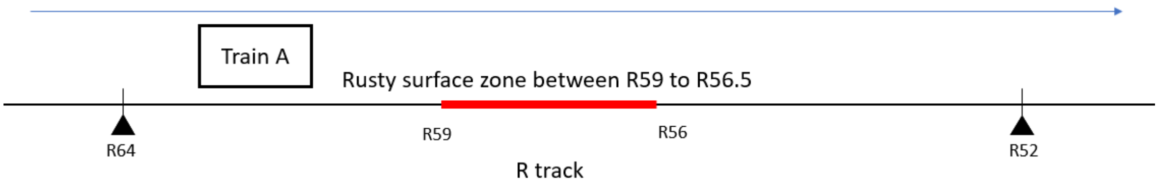


Figure 38. Test Case 11 Simulated Scenario 2

The third scenario, as shown in Figure 40, simulated the rusty surface observed from the outbound direction VBTC device, with the rusty surface length of approximately 1,500 feet (the train length was approximately 503 feet). The train entered at the R64 section at a speed of 20 mph, stopped at the R61 location, and then a shunt was created at the R59 location. The train then resumed forward movement and stopped at R57, the shunt was removed after a certain amount of time, and the train resumed forward movement and exited at R52 at the speed of 20 mph.

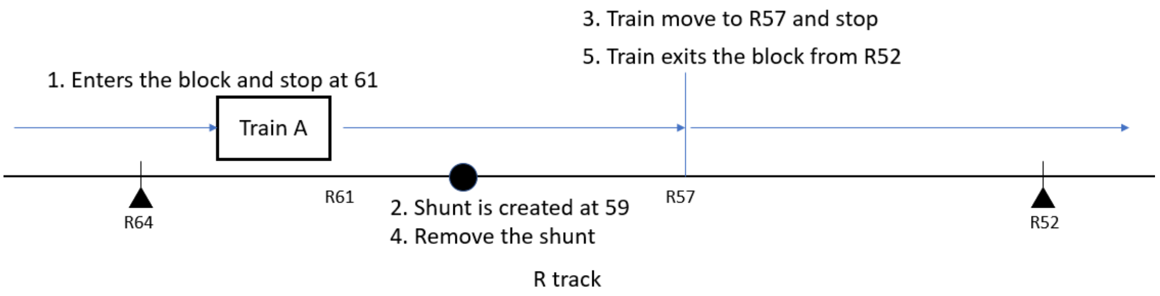


Figure 39. Test Case 11 Train Movement Diagram Scenario 3

In the scenario shown in Figure 41, a rusty surface was simulated between R59 and R57, so that from the R64 VBTC device, when the end of the train entered the simulated rusty zone, the shunting location would suddenly move from R59 to R56.5. Removing the shunt simulated this sudden shunt location change.

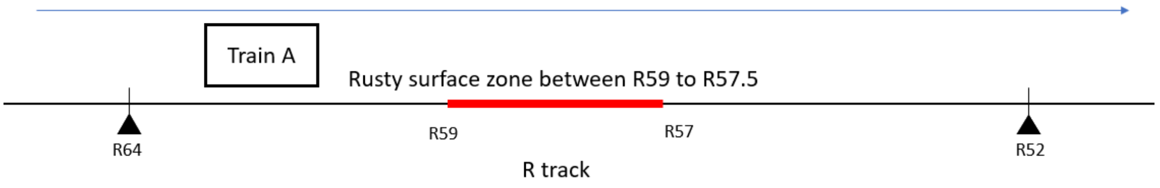


Figure 40. Test Case 11 Simulated Scenario 3

The data recorded for this test was obtained from the EC5 device data log and system log.

6.11.3 Recorded Test Results

Results are provided by device location, train movement, and corresponding VB status in Table 45, Table 46, and Table 47.

Table 58. R52 Data Log Record, R64 to R52, Scenario 1

Location	R52	**Begin**	R64	Note						
Train speed	20 MPH	**End**	R52							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A	T	T	T	T	T	T	T	T
1	Train enters the R block	16:38:32								
2	RVB4 occupied	16:38:32	F							
3	RVB3 occupied	16:40:32		F						
4	RVB2 occupied	16:46:50			F					
5	RVB1 occupied	16:57:18				F				
6	Train enters the L block	16:58:36								
7	LVB1-4 occupied	16:58:36					F	F	F	F
8	RVB1 clear	16:58:53	T							
9	Shunt removed	17:01:14								

Table 59. R64 Data Log Record, R64 to R52, Scenario 2

Location	R64	**Begin**	R64	Note		
Train speed	20 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	19:40:01				
2	VB1-4 occupied	19:40:01	F	F	F	F
3	VB1 clear	19:46:49	T			
4	System exits the VBTC mode	19:49:29		T		
5	Train exits the block	19:53:55				

Table 60. R64 Data Log Record, R64 to R52, Scenario 3

Location	R64	**Begin**	R64	Note		
Train speed	20 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	20:13:40				
2	VB1-4 occupied	20:13:40	F	F	F	F
3	VB1 clear	20:13:40	T			
4	System exits the VBTC mode	20:24:12		T		
5	Train exits the block	20:28:48				

6.11.4 Initial Analysis

From the current record from Scenario 1, shown in Figure 42, the train simulated the entry of the rusty rail zone at approximately 10:42 and exited the rusty zone at 10:47 (shunt created time). The measured TxC current for the two steps was 2.43 and 2.64. The system was running under VBTC mode during the whole process.

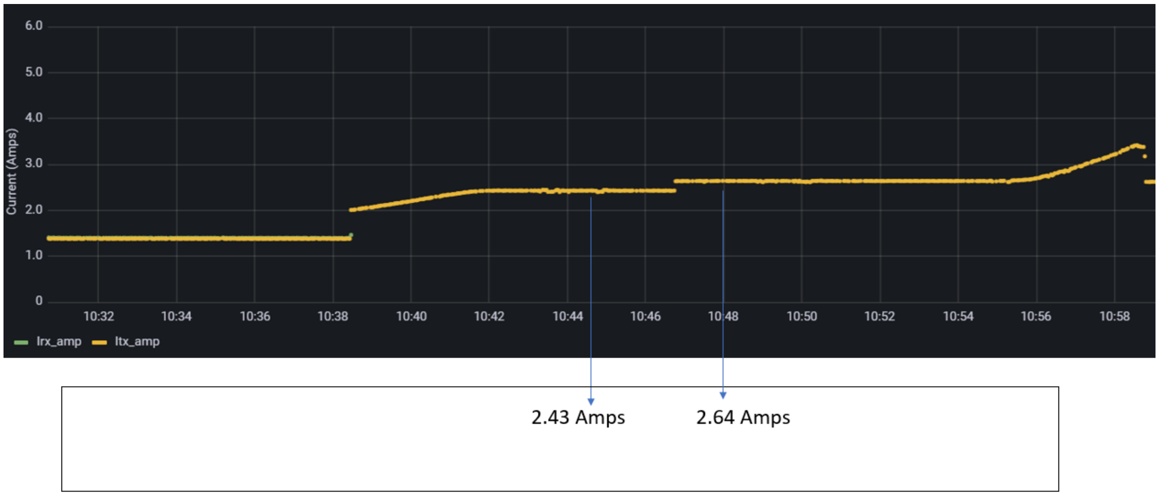


Figure 41. Test Case 11 TxC and RxC Record (R52 Data Record)

A similar current gap was obtained from Scenario 2 and Scenario 3. However, the system exited VBTC mode with the recorded reason “Bad Signal Quality,” so the system can be considered to offer protection against this loss of shunt scenario.

6.12 Wet Track Preparation

6.12.1 Purpose

This test was a preparation step for the wet track test. Train movement data recorded during this process can be used to observe the system performance under this extreme condition.

6.12.2 Test Case Procedures

In this test, as illustrated in Figure 43, a single locomotive with a tank car (20,643-gallon capacity) filled with water entered at R52 and started to dump water with the bottom valve. The train moved at a constant speed of 20 mph back and forth within the R52-R40 section until all the water was dispensed, estimated to be equal to 0.4 inches of rain.

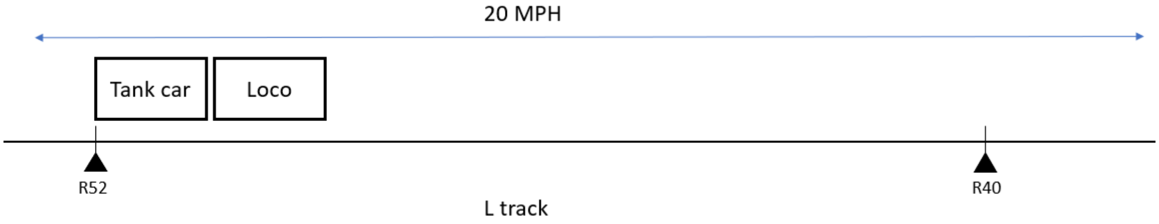


Figure 42. Test Case 12 Train Movement Diagram

6.12.3 Recorded Test Results and Initial Analysis

Table 48 and Table 49 provide results by device location, train movement, and corresponding VB status; Tx and Rx current record are shown in Figure 44.

Table 61. R40 Data Log Record, Multiple Movements

Location	R40	**Begin**	R52	Note	R52 to R40, R40 to R52, repeat twice	
Train speed	20 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the L block	18:40:59				
2	VB4 occupied	18:41:02	F			
3	VB3 occupied	18:49:03		F		
4	VB2 occupied	18:50:50			F	
5	VB1 occupied	18:52:31				F
6	VB1 clear	18:57:54				T
7	VB2 clear	18:59:41			T	
8	VB3 clear	19:01:34		T		
9	Train exits the L block	19:04:38				
10	VB4 clear	19:04:46	T			
11	Train enters the L block	19:05:09				
12	System exits the VBTC mode L	19:05:20	F	F	F	F
13	Train exits the L block	19:14:05				
14	System returns to VBTC mode L	19:14:12	T	T	T	T
15	Train enters the L block	19:14:12				
16	VB1-4 occupied	19:14:45	F	F	F	F
17	VB1 clear	19:18:09	T			
18	VB2 clear	19:19:56		T		
19	VB3 clear	19:22:45			T	
20	Train exits the L block	19:24:31				
21	VB4 clear	19:24:38				T

Table 62. R52 Data Log Record, Multiple Movements

Location	R52	**Begin**	R52	Note	R52 to R40, R40 to R52, repeat twice					
Train speed	20 MPH	**End**	R52							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A					T	T	T	T
1	Train enters the L block	18:41:02								
2	LVB 1-4 occupied	18:41:02					F	F	F	F
3	LVB 1 clear	18:49:23					T			
4	LVB 2 clear	18:51:18						T		
5	LVB 3 clear	18:53:29							T	
6	LVB 3 occupied	18:56:53							F	
7	LVB 2 occupied	18:58:43						F		
8	LVB 1 occupied	19:00:54					F			
9	Train exits the L block	19:04:38								
10	LVB 1-3 clear	19:04:41					T	T	T	
11	LVB 4 clear	19:04:45								T
12	Train enters the L block	19:05:08								
13	LVB 1-4 occupied	19:05:08					F	F	F	F
14	LVB 1 clear	19:08:48					T			
15	LVB 2 clear	19:11:01						T		
16	LVB 3 clear	19:13:21							T	
17	Train exits the L block	19:14:07								
18	LVB 4 clear	19:14:14								T
19	Train enters the L block	19:14:47								
20	LVB 4 occupied	19:14:47								F
21	LVB 3 occupied	19:17:35							F	
22	LVB 2 occupied	19:19:45						F		
23	LVB 1 occupied	19:22:21					F			
24	Train exits the L block	19:24:30								
25	LVB 1-3 clear	19:24:33					T	T	T	
26	LVB 4 clear	19:24:37								T

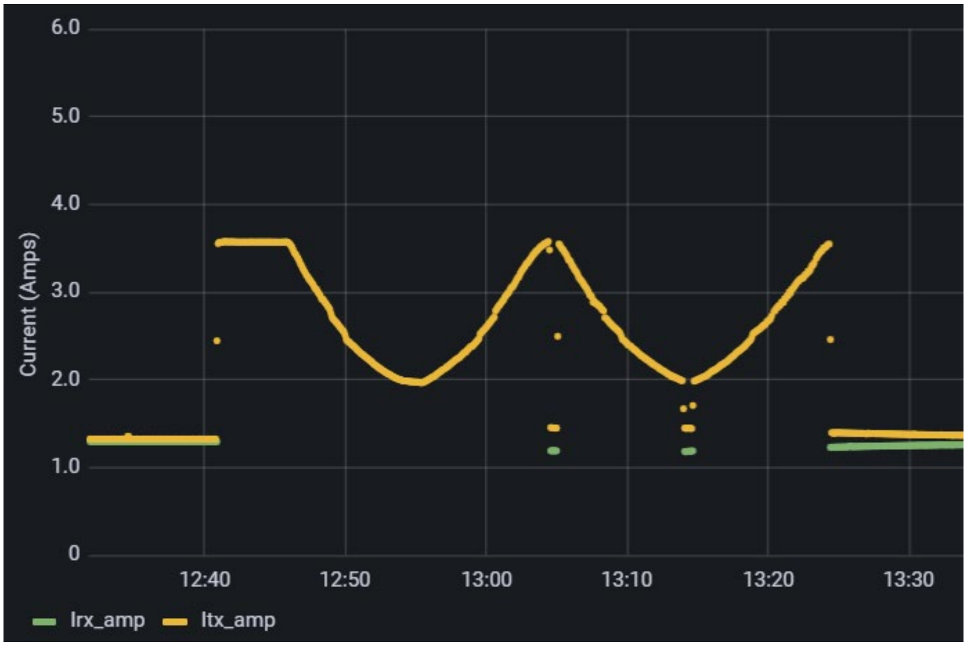


Figure 43. Test Case 12 Train Movement TxC and RxC Current Record

As observed from the current record, before the wetting process, the TxC (Yellow) and RxC (Green) current values were almost the same, and after the wetting process, a current gap appeared between the TxC and RxC, showing the current leakage through the wet track section.

6.13 Wet Track Test – Constant Speed Test

6.13.1 Purpose

Rain and other water-related environmental conditions can impact track circuit performance. Thus, a test under wet track conditions was set up to simulate this operational environment. The test case results were compared to the system performance under normal weather conditions.

6.13.2 Test Case Procedures

The train consist comprised nine railcars and a single locomotive and performed the basic constant speed train movement within the wetted test section (Figure 45).

In this test, the VB Scale Factor was set to 0 percent, the system's default setting. The train, with GPS equipment on the locomotive, entered at R52 at a speed of 30 mph and maintained a constant speed movement until exiting at the R40 section. The same process was repeated from R40 to R52.

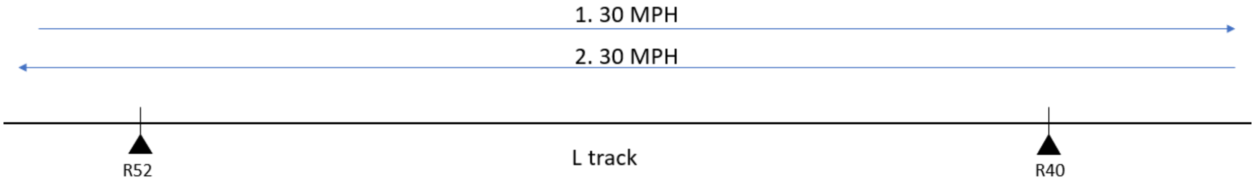


Figure 44. Test Case 13 Train Movement Diagram

The data recorded for this test was obtained from the EC5 device data log and system log. Compared with pre-measured ideal virtual block boundary and GPS data, the distance from the ideal virtual block boundary to the rear-of-train location was considered as system accuracy detection results.

6.13.3 Recorded Test Results and Initial Analysis

Results are provided by device location, train movement, and corresponding VB status in Table 50 through Table 54.

Table 63. R40 Data Log Record, R52 to R40

Location	R40	**Begin**	R52	Note	30 mph, VBF=0	
Train speed	30 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	20:01:56				
2	VB4 occupied	20:01:59				F
3	VB3 occupied	20:03:39			F	
4	VB2 occupied	20:04:45		F		
5	VB1 occupied	20:05:42	F			
6	Train exits the block	20:06:38				
7	VB1-VB3 clear	20:06:39	T	T	T	
8	VB4 clear	20:06:46				T

Table 64. R40 Data Log Record, R40 to R52

Location	R40	**Begin**	R40	Note	30 mph, VBF=0	
Train speed	30 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	20:18:35				
2	VB1-4 occupied	20:18:35	F	F	F	F
3	VB1 clear	20:20:28	T			
4	VB2 clear	20:21:25		T		
5	VB3 clear	20:22:32			T	
6	Train exits the block	20:23:17				
7	VB4 clear	20:23:24				T

Table 65. R52 Data Log Record, R52 to R40

Location	R52	**Begin**	R52	Note	30 mph, VBF=0					
Train speed	20 MPH	**End**	R40							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A					T	T	T	T
1	Train enters the L block	20:01:56								
2	LVB 1-4 occupied	20:01:56					F	F	F	F
3	LVB 1 clear	20:03:52					T			
4	LVB 2 clear	20:05:00						T		
5	LVB 3 clear	20:06:05							T	
6	Train exits the L block	20:06:36								
7	LVB 4 clear	20:06:43								T

Table 66. R52 Data Log Record, R52 to R40

Location	R52	Begin	R40	Note	30 mph, VBF=0					
Train speed	20 MPH	End	R52							
Event	Event description	Time	RVB1	RVB2	RVB3	RVB4	LVB1	LVB2	LVB3	LVB4
0	Initial Status	N/A					T	T	T	T
1	Train enters the L block	20:18:33								
2	LVB 4 occupied	20:18:36					F			
3	LVB 3 occupied	20:20:02						F		
4	LVB 2 occupied	20:21:09							F	
5	LVB 1 occupied	20:22:12								F
6	Train exits the L block	20:23:17								
7	LVB 1-3 clear	20:23:18					T	T	T	
8	LVB 4 clear	20:23:24								T

Table 67. Exit Accuracy Detected for R52 and R40

Location	R40							
Test Run.	Train speed	enter	exit	VB1	VB2	VB3	VB4	Average
2	30	40	52	1666	1144	1150	N/A	1320
Location	R52							
Test Run.	Train speed	enter	exit	LVB1	LVB2	LVB3	LVB4	Average
1	30	52	40	2259	2314	2137	N/A	2237

As can be observed, the detection of the block status performs normally when the system is running under VB mode during train movement with wet track condition.

6.14 Wet Track Test – Broken Rail Test

6.14.1 Purpose

Since wet track conditions can affect the track circuit performance, a broken rail test was repeated to compare with results from normal weather condition testing.

6.14.2 Test Case Procedures

In this test, the train consist comprised 9 rail cars and a single locomotive, the VB Scale Factor was set to 0 percent, and the broken rail was set up at the R46 IJ location. Two train movements were performed during this test, as shown in Figure 46 and Figure 47.

In the first movement, the train entered at R52 at a speed of 20 mph and maintained constant speed movement until exiting at R40. When the train was overlapping the R46 IJ, the BR was triggered at the R46 IJ location.

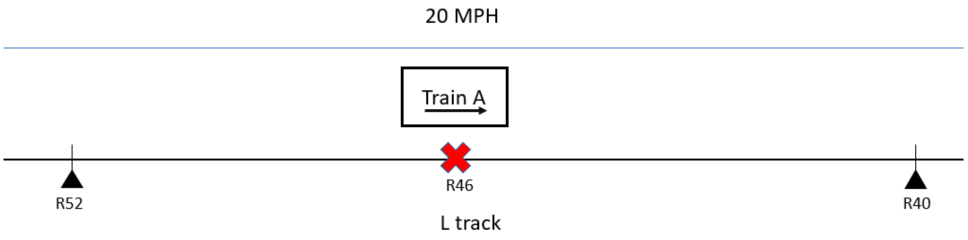


Figure 45. First Broken Rail and Train Location

In the second movement, the train entered at R40 at a speed of 20 mph and performed a constant speed movement until exiting at R64. When the train was located at R51, the BR was triggered at the R46 IJ location.

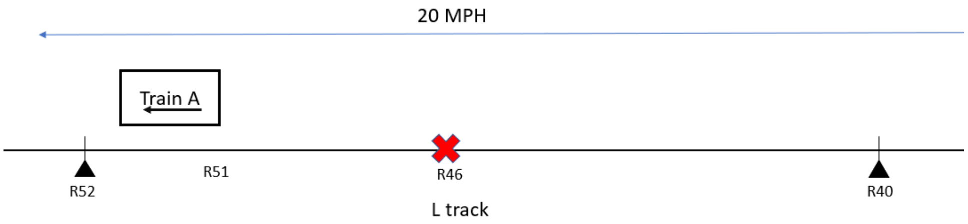


Figure 46. Second Broken Rail and Train Location

The data recorded for this test was obtained from the EC5 device data log and system log.

6.14.3 Recorded Test Results

Table 55 through Table 58 provide results by device location, train movement, and corresponding VB status.

Table 68. R40 Data Log Record, R52 to R40

Location	R40	**Begin**	R52	Note	30 mph, VBF=0	
Train speed	30 mph	**End**	R40			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	20:48:23				
2	System exits the VBTC mode	20:48:34	F	F	F	F
3	BR detected, no location report	20:55:25				
4	BR recovered	20:55:41				
5	System returns to VBTC mode	20:55:49	T	T	T	T

Table 69. R40 Data Log Record, R40 to R52

Location	R40	**Begin**	R40	Note	30 mph, VBF=0	
Train speed	30 mph	**End**	R52			
Event	**Event description**	**Time**	**VB1**	**VB2**	**VB3**	**VB4**
0	Initial Status	N/A	T	T	T	T
1	Train enters the block	21:00:07				
2	VB1-4 occupied	21:00:07	F	F	F	F
3	VB1 clear	21:02:53	T			
4	VB2 clear	21:04:18		T		
5	VB3 clear	21:05:58			T	
6	BR detected, location reported	21:06:22				
7	System exits the VBTC mode	21:06:22	F	F	F	
8	BR recovered	21:07:40				
9	System returns to VBTC mode	21:07:47	T	T	T	T

Table 70. R52 Data Log Record, R52 to R40

Location	R52	**Begin**	R52	Note	30 mph, VBF=0					
Train speed	20 MPH	**End**	R40							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A					T	T	T	T
1	Train enters the L block	20:48:21								
2	System exits the VBTC mode L	20:48:33					F	F	F	F
3	BR detected, no location report	20:52:06								
4	BR recovered	20:55:41								
5	System returns to VBTC mode L	20:55:49					T	T	T	T

Table 71. R52 Data Log Record, R40 to R52

Location	R52	**Begin**	R40	Note	30 mph, VBF=0					
Train speed	20 MPH	**End**	R52							
Event	**Event description**	**Time**	**RVB1**	**RVB2**	**RVB3**	**RVB4**	**LVB1**	**LVB2**	**LVB3**	**LVB4**
0	Initial Status	N/A					T	T	T	T
1	Train enters the L block	21:00:05								
2	LVB 4 occupied	21:00:08					F			
3	LVB 3 occupied	21:02:16						F		
4	LVB 2 occupied	21:03:49							F	
5	LVB 1 occupied	21:05:25								F
6	BR detected	21:07:05								
7	System exits the VBTC mode L	21:07:06								
8	BR recovered	21:07:40								
9	System returns to VBTC mode L	21:07:47					T	T	T	T

6.14.4 Initial Analysis

During the R52 to R40 train movement, R52 served as the outbound side. During this movement, VBTC mode was inactive at R52, due to the following reason:

Location Disabled - Far Entry Threshold Not Met

Since VBTC mode was inactive, the system could detect the broken rail but could not offer the location report.

For the R40 to R52 train movement, R40 served as the outbound side. During this movement, one broken rail event was created and detected. The detailed information offered by the system is as follows:

- The system exited VBTC mode after the rail break was detected with the following location report: "Slot 1 Track 1 (LTKO1) Track Integrity Lost at 95.9(11,412 feet)." This location shows the BR based on the EOT location R51, while the actual BR location was at R46. Similar detection results were obtained for the simulated spontaneous rail break test under normal track conditions, and the cause is the same as that test case.

6.15 Wet Track Test – Ballast Condition Test

6.15.1 Purpose

As discovered in previous test case results, when the track condition is changed significantly due to moisture or other environmental factors, the system may have a higher chance of exiting VBTC mode during train operation. To analyze this ballast change condition, a wet track scenario was created and tested.

6.15.2 Test Case Procedures

In this test, the wet track process was similar to that in Test Case 12. However, to better simulate a light rain fall, the valve of the tank car was set to run with less volume so it took eight train runs to dump all the water (as opposed to the four train runs taken for Test Case 12). The train consist comprised nine railcars and a single locomotive and the VB Scale Factor was set to 0 percent.

In this test, after wetting the track with water, the consist performed the train movement test with constant speed. As shown in Figure 48, the locomotive entered at R64 at a speed of 30 mph and maintained constant speed until it exited the block at R52. The same procedure was repeated five times.

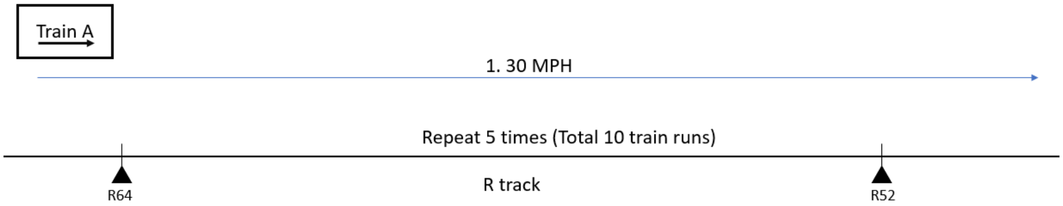


Figure 47. Test Case 15 Train Movement Diagram

6.15.3 Recorded Test Results

Results are presented in Table 59, Figure 49, and Figure 50.

Table 72. VBTC Mode Operation Record for R64 and R52

Train run	From	To	R52 VBTC	R64 VBTC	Enter time	Exit time
1	R64	R40	On	On	17:49:33	17:54:14
2	R40	R64	On	On	18:11:17	18:15:55
3	R64	R40	On	On	18:33:51	18:38:32
4	R40	R64	On	On	18:55:53	19:00:29
5	R64	R40	On	On	19:17:52	19:22:33

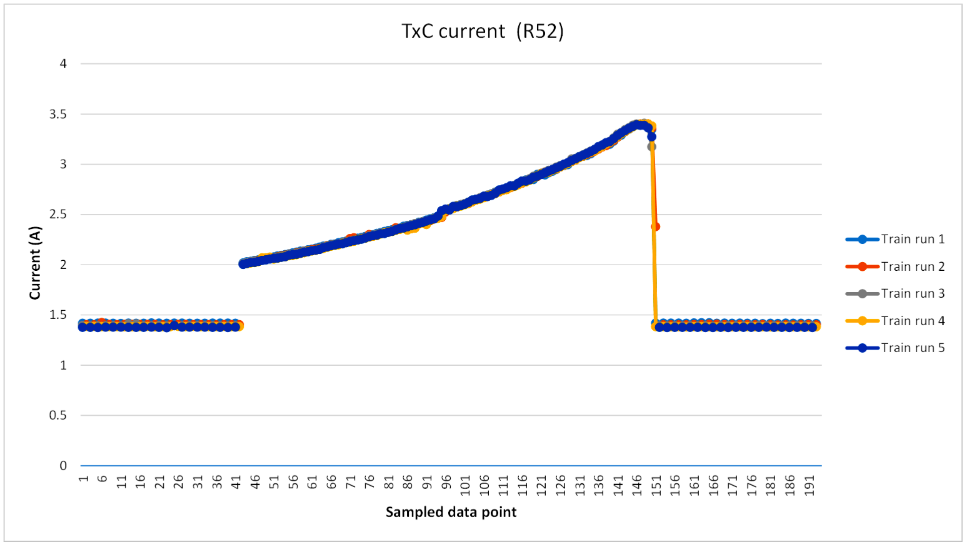


Figure 48. TxC Current Measurements per Train Run, R52

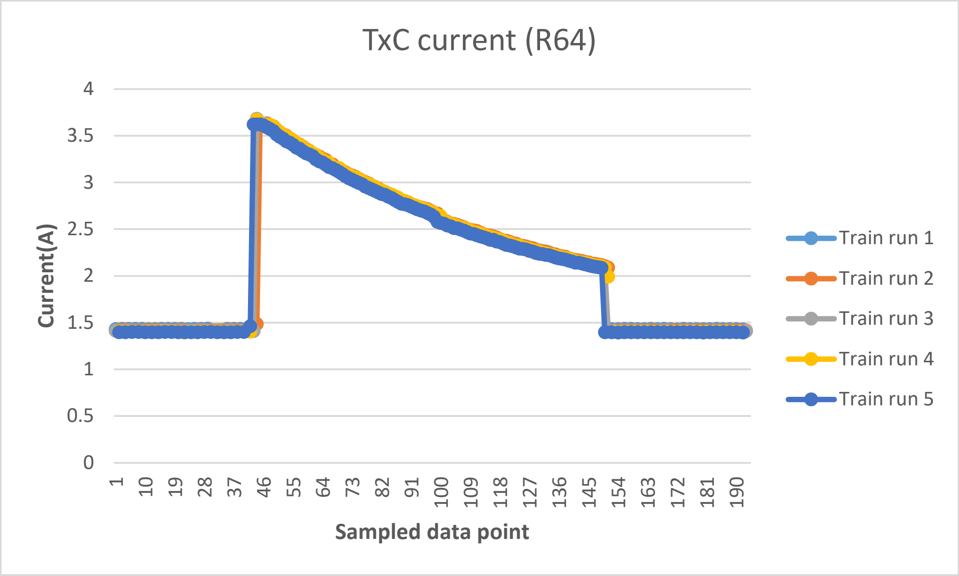


Figure 49. TxC Current Measurements per Train Run, R64

6.15.4 Initial Analysis

The test results show that as the moisture decreased with time, the TxC current decreased (see Figure 51). Since the VBTC TxC current has an active threshold, further research is suggested to analyze how significantly the moisture affects the VBTC system performance.

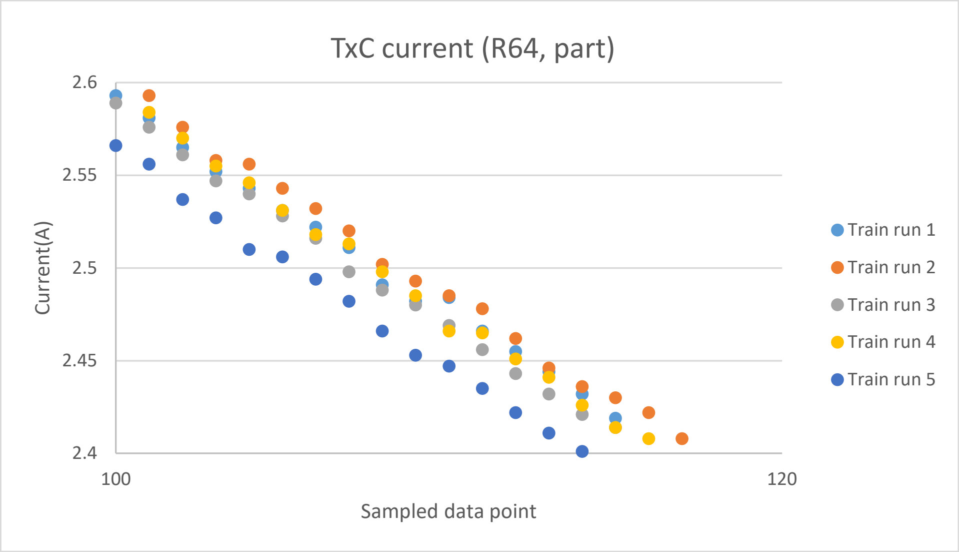


Figure 50. TxC Current Measurements per Train Run (Zoomed In), R64

7. Summary and Findings During the Calibration and Field Test

In this section, some key findings are presented, including a summary of the basic performance and key performance analysis.

7.1 Basic System Performance

The research team observed the ElectoLogIXS/EC5 device with VBTC functionality tested for this project performing the essential functions for the VBTC concept under several typical operation scenarios. These scenarios included constant speed movement, changing movement direction within a single physical block, pull-apart protection, double occupancy within a single physical block, and power outage.

In the scenarios involving train acceleration within a physical block, the team observed two instances of the system exiting VBTC mode. These occurrences are likely due to the combination of acceleration and possible inconsistent shunting of the test train.

7.2 VB Scale Factor Related Performance

Since the VB Scale Factor directly affects system capacity performance, several test cases were conducted to analyze performance with varying VB Scale Factors. During the VB Scale Factor test cases, the following observations were made:

1. The higher the speed of train movement, the greater the impact of delay in detecting the track block status, since the status of a virtual block transitioning from Occupied to Clear is delayed by the combination of the safety buffer, system processing time, and the debounce buffer (a function used to eliminate the effects of erratic signals). This was observed based on a comparison of the GPS train location log with the virtual block status log, both of which were time stamped.
2. Increasing the VB Scale Factor can decrease the accuracy of the virtual block status detection. When increasing the VB Scale Factor from 50 to 255 percent, the team observed a significant increase in the distance between EOT to the ideal virtual block boundary related to that status when the virtual block track status changed. This translates into excess headway for a following train.
3. The detection inaccuracy can be longer than a virtual block length when the VB Scale Factor is set to 255 percent. Another observation from one test was that no virtual blocks were reported Clear by one device until the train exited the physical block (then all VB status within that physical block reported Clear at the same time), even though the VBTC system log showed that this device was still running under VB mode.

7.3 System Performance Under Various Weather Conditions

The EC5 device with VBTC functionality was tested under various weather conditions, and the following findings were observed:

1. During the calibration process, a calibration train movement has a higher chance of being considered invalid during or shortly after rainy weather when track conditions are wet. The reason for the train movement to be considered as invalid is recorded as “Invalid

Outbound Move for Calibration - Far Shunt TxC" or "Invalid Inbound Move for Calibration - Far Shunt TxC."

2. During the test process, after the system was fully calibrated, the system failed the threshold check (resulting in the system deactivating VBTC mode) more often for train movements over track that had recently incurred a significant condition change (i.e., from dry to wet). Deactivating VBTC mode is expected behavior and impacts potential capacity gains but does not affect operational safety. However, the supplier indicated that the EC5 device with VBTC functionality can adapt to changing conditions by continuously updating system calibration so that these operational impacts are temporary.

Observations were recorded in TTC track conditions with a relatively modest amount of moisture applied to the track, i.e., the equivalent of approximately 0.4 inch of rain. Setting the VB Scale Factor to a higher value in locations that experience more rain might help relieve this problem. However, it could be that VBTC performance in locations that experience significant amounts of rain could be significantly impacted until enough trains have passed and updated the calibration. Further testing is recommended with higher moisture levels to analyze this issue.

7.4 Broken Rail Detection and Non-Vital Broken Rail Location Report

The ElectoLogIXS/EC5 device with VBTC functionality, with the system Exec and boot build provided by the supplier, can detect a rail break within an occupied block and can proactively exit VBTC mode to protect operational safety. The system also can offer broken rail protection under wet track conditions as created in field testing.

The location reported in association with a rail break is non-vital information recorded within the system log. This location information is only valid in the case of a rail break that occurs under a moving train since it is based on the estimated rear-of-train location when the rail break is detected by VBTC (i.e., when the train has just cleared the break). However, this location information cannot be used for vital purposes because of the risk of misreporting during a spontaneous rail break scenario, as shown in Test Case 9 and Test Case 14.

7.5 Performance for Loss of Shunt Issue Due to Simulated Rusty Surface

A loss of shunt scenario due to a simulated rusty rail surface was examined in Test Case 11. For the tested outbound scenarios, the system exited VBTC mode in simulated rusty rail surface zones with the length of 1,500 feet and 2,500 feet. In this way, the VBTC system offered protection for those scenarios.

7.6 Conclusion

The devices tested at TTC performed essential VBTC functions in most test cases. VBTC can therefore be expected to provide a means to reduce train headways and increase the network traffic capacity under the common operational scenarios tested. However, additional evaluation under a broader range of conditions, both operational and environmental, is recommended to fully evaluate the performance.

Acronyms & Abbreviations

Acronym	**Definition**
BR	Broken rail
DC	Direct current
EOT	End-Of-Train
GPS	Global Positioning System
HOT	Head-Of-Train
IJ	Insulated joint
LOS	Loss of shunt
MDT	Mountain Daylight Time
RTT	Railroad Test Track
RxC	Receive current
TTC	Transportation Technology Center
TxC	Transmit current
UTC	Coordinated Universal Time
VB	Virtual Block
VBTC	Virtual Block Track Circuit
WSDMM	Wayside System Data Management Module
WSM	Wayside Status Message

Appendix C.
Capacity Analysis for Virtual Block Track Circuits Assessment

Contents

1. Background and Scope

This document provides an analysis of train operation performance when Virtual Block Track Circuit (VBTC) is implemented in conjunction with Overlay PTC (O-PTC), Enhanced Overlay PTC (EO-PTC), or Quasi Moving Block (QMB) train control methods. The analysis was developed considering the minimum achievable separation for a pair of trains in a following move in ideal theoretical operational scenarios. The performance of trains when using VBTC was compared with the use of conventional track circuits under the same train control method, with track circuits split in half (i.e., half the length of the original track circuit), and with Full Moving Block (FMB). The analysis considered different train types, track speeds, and operating conditions. An algorithm (a potential basis for a pacing algorithm) that attempts to minimize train separation for various scenarios resulting in minimized train headways was proposed.

The analysis provides an estimation of potential capacity gains in terms of the minimum achievable separation for a pair of trains in a following move, which is the scenario in which the largest readily quantifiable benefit of VBTC is expected. The analysis did not include an estimation of railroad network capacity gains.

The analysis included typical or estimated latencies and margins introduced by multiple system components during the operation of following train moves.

2. VBTC Capacity Analysis Overview

The capacity of a railroad track can be defined in various ways, depending upon the ratio of trains operating in one direction versus the other, train velocity, whether fleeting can be used, track configuration, train characteristics, and other considerations. For the purposes of this study, track capacity is defined as the number of trains allowed to operate on the same track, at the same time, in the same direction, with no opposing moves, while maintaining track speed; this is the scenario where the largest readily quantifiable benefit of VBTC is expected. Train headway, which is a major factor that affects capacity, depends mainly on the separation distance required between trains (i.e., train separation between the rear of a leading train and the front of a following train) to maintain both safe operation and the track's maximum authorized speed (MAS). This analysis estimates the theoretical minimum separation between trains in following moves, which provides insight into potential capacity gains that can be obtained under certain operational scenarios and system configurations. Various train control methods were considered in this analysis. Comparisons between the use of VBTC and conventional track circuits are quantified to assess potential capacity gains.

O-PTC with four-aspect signaling is the base case where conventional track circuits are used. EO-PTC is an enhancement of O-PTC where no premature deceleration is required at a yellow signal as long as the train does not reach its braking distance from a red signal (i.e., a train decelerates based on reaching the braking distance plus margin from a signal displaying Restricting or Stop). The Basic QMB (B-QMB) train control method adapts a moving block concept to update movement authorities while depending on track circuits to ensure track integrity. In B-QMB operations with conventional track circuits, trains can enter an occupied physical block only at or below Restricted Speed during a following move. In advanced QMB operations, where a technology such as VBTC is used, a following train may be permitted to enter an occupied physical block at MAS up to the boundary of the last occupied virtual block (VB) by the rear end of a leading train (plus safety buffer) before the following train enters the physical track circuit. This study analyzes the minimum separation between trains operating in following moves at a constant speed that prevents a following train from reaching the boundaries where speed restrictions are imposed, causing inefficient operation and a loss of capacity.

An analytical model was developed to calculate train headways based on the minimum separation between a pair of trains for an ideal following move scenario (i.e., not a network analysis). The analysis considered different train types, track speeds, track circuit lengths, and operating conditions. The analysis also included latency or margins introduced by multiple system components during the trains' following moves. The actual values for these margins can change based on the actual operating conditions on track; therefore, the results can change accordingly. The methods and equations used are presented so that the analysis can be readily applied to following move scenarios with different values for the relevant parameters.

3. Minimum Train Separation for Optimal Operation

3.1 Methodology

To maximize capacity gains, train separation in following moves should be minimized, while abiding by train movement authority limits and other factors, such as those related to margins. An optimal operation that maximizes capacity is where trains operate in following moves as closely as possible, but without ever reaching their braking distances (i.e., never having to unnecessarily decelerate due to incurring enforcement by PTC when the train gets within braking distance of speed or Stop targets).

In a scenario where a train reaches its braking distance in a following move, the train would have to decelerate and reach a full stop or operate under a Restricted Speed Restriction (RSR) until it is allowed to accelerate again and resume track speed. The deceleration caused by the train in this scenario can impose major losses on traffic performance as well as energy efficiency, both of which can be significant in areas with high train traffic density. On the other hand, keeping unnecessary large headways prevents the realization of potential track capacity gains.

This undesired train deceleration/acceleration sequence can be avoided by maintaining a certain minimum separation distance between trains in a following move. This possibly could be accomplished using a fleeting operation, where the leading train is operating at constant speed and the following train is capable of determining the location where it would have to start reducing speed based on various factors, such as the speed of the leading train, the track circuit block length, the next occupied block (or virtual block where VBTC is deployed), the distance from its movement authority (PTC Exclusive Authority or PTCEA), “To” limit (if trains are operating under QMB or FMB), and safety margins. This operation can be further refined if the speed of the leading train is provided to, or can be inferred by, the following train, so it can predict when the leading train would likely leave that block. In such cases, the objective is to have both trains operating at approximately the same speed with almost constant pacing so that changes in the speed of the leading train will directly impact the speed of the following train, thereby establishing a Minimum Steady State Separation (Min SSS) condition.

This analysis investigates the Min SSS required for various train control methods (i.e., O-PTC, EO-PTC, and QMB) to assess the capacity benefits when VBTC is used instead of conventional track circuits. The Min SSS equations are developed for each train control method when operating with conventional track circuits and when operating with VBTC. After that, various scenarios that include different track circuit block lengths, different train types, and track speeds are evaluated to find the Min SSS distance required when operating with and without VBTC. Finally, results for each scenario when operating with and without VBTC are compared to identify the potential capacity gains (in terms of train headway reduction) introduced with the use of VBTC during following moves. The analysis also includes a comparison of Min SSS results between FMB and train control methods that are operating with VBTC.

3.1.1 Min SSS for O-PTC

In signaled territory, the Min SSS for trains operating with O-PTC active is determined by the signaling system. In four-aspect signaling, the track circuit length must be at least half the braking distance of the train that has the largest braking distance at track speed (e.g., the heaviest train operating at MAS). In many cases, signals are spaced even further apart. On most Class 1 railroads, a train operating on four-aspect signaling is required to begin decelerating to 40 mph at a flashing yellow signal, begin decelerating to 30 mph (or to 40 mph for passenger trains) at a solid yellow signal, and be able to stop at a red signal. As a result, the Min SSS between two trains following one another in O-PTC territory is approximately three blocks. This distance allows the leading train to clear the third block ahead and change the aspect of the next signal ahead of the following train from flashing yellow to green just before the following train reaches the signal that just turned green.

On the other hand, a train operating on three-aspect signaling is required to start decelerating at a yellow signal and strictly be able to stop at a subsequent red signal. For three-aspect signaling, a track circuit must be at least the length of the braking distance of a train that has the longest braking distance at MAS. This requires a Min SSS of two physical blocks, a distance that allows another train to clear the second block ahead and change the signal aspect from yellow to green by the time the following train reaches the signal that just turned green.

Figure 1 illustrates Min SSS for three-aspect and four-aspect signaling under ideal conditions (i.e., assuming no implementation-specific delays). The "excess spacing" (i.e., spacing beyond that required to stop a following train before it reaches the train ahead) is at least one block in both cases. However, the blocks are twice as long in three-aspect signaling. In most conventional signaling scenarios, the excess spacing is even greater than the ideal one-block distance. This is because four-aspect signals are often spaced further apart than one-half of the worst-case braking distance (or spaced further apart than the worst-case braking distance for three-aspect signaling) to reduce the life cycle cost of the signaling system. Delays associated with coded track circuits (known as "tumble down" time) and communications delay further add to train separation.

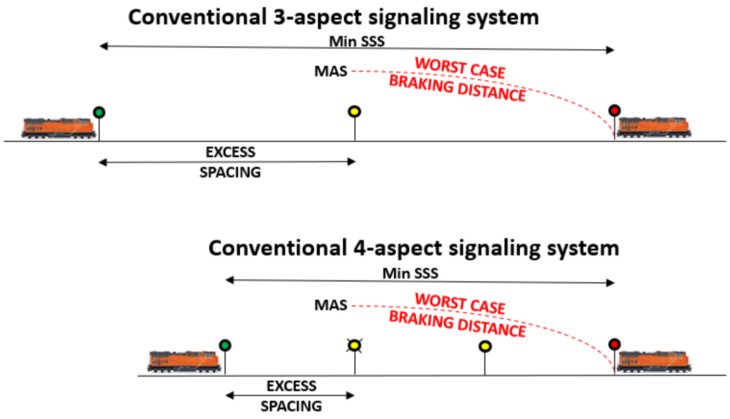


Figure 51. Ideal Min SSS for Three-aspect and Four-aspect Signaling

The Min SSS for O-PTC operation with four-aspect and three-aspect signaling, indicated by Min $\text{SSS}_{\text{O-PTC\_4b}}$ and Min $\text{SSS}_{\text{O-PTC\_3b}}$, are given in (1) and (2), respectively.

$$\text{Min SSS}_{\text{O-PTC\_4b}} = 3\,(\text{TC}_{\text{L}}) + \text{M}_{\text{TC}} + 2\,(\text{T}_{\text{b-b}}) + \text{EPM} \tag{1}$$

$$\text{Min SSS}_{\text{O-PTC\_3b}} = 2\,(\text{TC}_{\text{L}}) + \text{M}_{\text{TC}} + \text{T}_{\text{b-b}} + \text{EPM} \tag{2}$$

$$\text{where } \text{M}_{\text{TC}} = [(\text{T}_{\text{TCr}} + \text{T}_{\text{WSM}}) * \text{S}_{\text{L-trn}}/3600] \tag{3}$$

The factors included in equation (1) are:

- TC_L – Length of the track circuit (in miles)
- M_{TC} – Time (in seconds) required to convey to the following train that the track circuit (or VB in case of VBTC) in a block is Clear, converted to distance (based on leading train's speed)
- $T_{b\text{-}b}$ – Time (in seconds) required to convey to the next block the status change to Clear of the previously occupied block in a cascading manner; this applies to one block in three-aspect signaling and two blocks for four-aspect signaling and is assumed to be 5.2 seconds per block
- EPM – Enforcement Prevention Margin (in seconds), which is set between the warning time and the limit of predictive enforcement, assumed to be 20 seconds

The margin components for M_{TC}, given in (3), include the following:

- T_{TCr} – Track circuit release time (in seconds), i.e., time that it takes for the circuitry to change the track circuit indication from more restrictive to less restrictive after an occupancy is cleared
- T_{WSM} – Wayside Status Message (WSM) periodic broadcast time (in seconds)
- $S_{L\text{-trn}}$ – Speed of the leading train (in mph)

3.1.2 Minimum SSS for EO-PTC and B-QMB

In B-QMB operation, a train needs to be able stop before entering an occupied block, although, in most cases, it can enter an intermediate block at Restricted Speed. This requires the train to start decelerating no later than when it reaches its predicted braking distance from an occupied block. In actual operations, a crew will start to decelerate some amount of time (a margin given here as EPM) before their train reaches its predicted braking distance from an occupied block to avoid a PTC enforcement and possibly to allow for split-reduction braking rather than full-service braking. In QMB (as in FMB), a leading train needs to automatically roll-up its movement authority (i.e., PTCEA) to free up a section of track that a following train needs to occupy. Moreover, the leading train needs to roll-up its PTCEA frequently enough to allow a following train to follow closely enough according to the Min SSS to avoid impacting capacity. The PTCEA roll-up period plus the time to process and send a new PTCEA to a closely following train should be much less than the time needed to traverse a block at the speed of trains that are in a following move.

EO-PTC alleviates the requirement to start decelerating at flashing yellow and yellow signals; it only requires the train to be able to reach a full stop at a red signal. Although EO-PTC and B-QMB are distinct train control methods, they achieve the same Min SSS distance, assuming that PTCEA roll-ups in B-QMB are frequent enough to not add margin to train separation. Therefore, throughout this report, all EO-PTC headway/capacity analyses and results are applicable to B-QMB with conventional track circuits.

The Min SSS for EO-PTC (Min $SSS_{EO\text{-}PTC}$), also for the Min SSS for B-QMB, is given in (4), where EPM is an enforcement prevention margin.

$$\text{Min } SSS_{B\text{-}QMB} = TC_L + BC_0 + M_{TC} + EPM \tag{4}$$

It is denoted that BC_0 is the full-service braking distance to a full stop.

3.1.3 Minimum SSS for EO-PTC or B-QMB with VBTC

As with conventional track circuits and signaling, achieving maximum capacity gains while operating with VBTC requires a following train to maintain a Min SSS from a leading train in a following move operation. However, VBTC permits a shorter Min SSS than conventional track circuits, translating into a traffic capacity gain.

Where VBTC is operating, there are different factors that affect Min SSS that include:

- The track circuit (i.e., "block") physical length
- The length of a VB (i.e., the length of the physical block divided by the number of VBs in that block)
- The safety buffer (SB) added to VBs within the track circuit beyond the VB boundary
- The time delay for the status change of a VB or a physical block (occupied to Clear) to be indicated and communicated to a following train
- The EPM
- The PTC-predicted full-service braking distance of the train to a full stop

If the following train reaches its predicted braking distance from a VB that is reporting Not Clear status, PTC will enforce it to decelerate to a full stop and then not exceed RSR until the leading train clears the block, which will cause a larger headway separation between the two trains than if the following train had not reached its predicted braking distance from the block reporting Not Clear (see Figure 2). If the following train passes the last known location of the leading train (i.e., the last VB occupied by the leading train) at the time the following train entered the occupied physical block and before the leading train clears the block, the following train will need to enter the block at RSR and maintain RSR until the end of that block, even if the leading train has cleared it. This is because the leading train could have caused a broken rail immediately after the last known occupied location, and VBTC would not be able to detect it because VBTC cannot detect broken rails between two trains in the same block.

VBTC can detect some broken rails in an occupied block (specifically a break between an end of a physical block and the nearest shunting axle of an occupancy) if there is no rail break and no occupancy in at least the first VB on the entry end of the physical block, which allows a following train to enter an occupied block at MAS. Since VBTC cannot detect a rail break between two trains occupying the same block, the following train must maintain a separation of no less than half the track circuit physical length (plus other margins and additional separation caused by the braking distance) to allow the leading train to clear the block before the following train reaches its predictive braking distance limit and incurs PTC enforcement. Depending on the braking distance of the following train and SB of VBTC, the Min SSS when operating with VBTC can be dictated by one of two equations (5, 6), as explained below. These Min SSS equations for operating with VBTC are based on an application code design in which each end of the track circuit reports two VB statuses on each side (i.e., the device at the right end of the track circuit reports VB3 and VB4 statuses of that physical block and VB1 and VB2 statuses of the following physical block, while the device at the left end reports statuses of VB1 and VB2 of that physical block and VB3 and VB4 of the previous physical block).

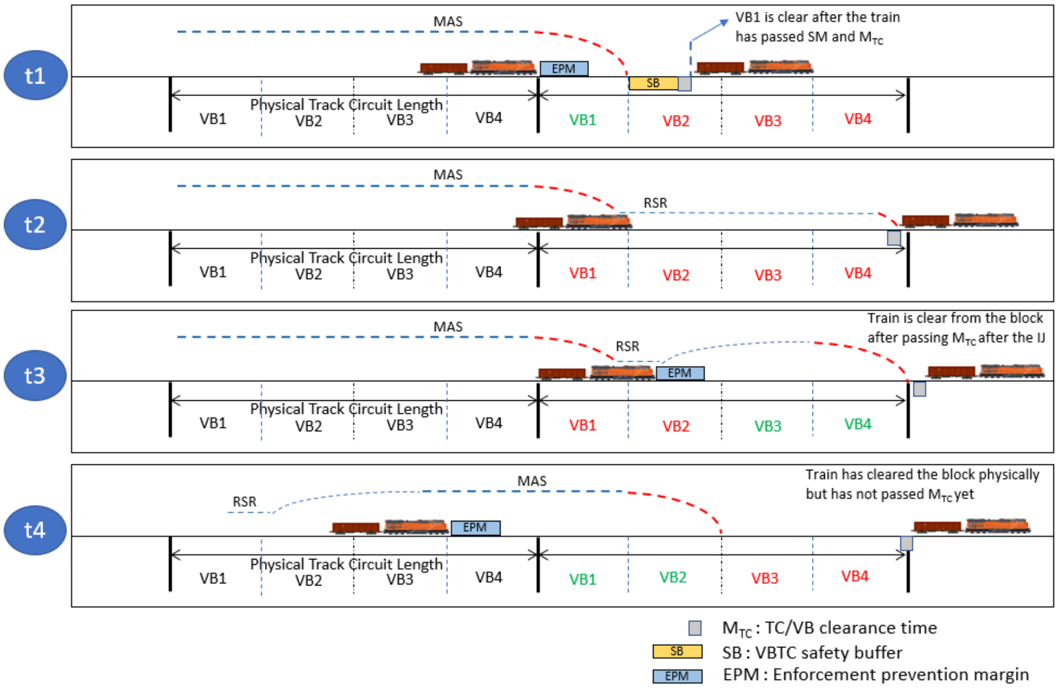


Figure 52. Example for Train Speed Profile and Excess Separation Caused When a Following Train Gets Closer Than Min SSS from the Leading Train During Operation with VBTC

For trains with a short braking distance (i.e., the predicted braking distance is less than the SB), operating in a following move behind a leading train at the same speed requires the following train to maintain additional separation distance from the SB to allow the leading train to clear the second VB before the following train enters that physical block. This is to avoid reaching its predicted braking distance limit with the target set at the boundary of the first VB. In this case, VBTC margins, such as SB plus distance traveled during the system processing and communication delays (here assumed to be M_{TC}), as well as train engineer margin to control train speed (i.e., EPM), must be added to half the track circuit physical length to determine the total separation distance. This is illustrated in Figure 3 and Figure 4 and in equation (5). It is worth noting that the SM for VBTC is the distance that the rear of a train requires to travel beyond a VB boundary for VBTC to indicate that the VB is Clear.

When the braking curve distance of the train is large enough (i.e., the predicted braking distance is equal to or greater than the SB), the braking distance to full stop plus margins (i.e., time to convey VB or physical block status change (M_{TC}) and EPM) must be added to half the track circuit physical length to allow proceeding at MAS in a following scenario. This is illustrated in Figure 4 and in equation (6).

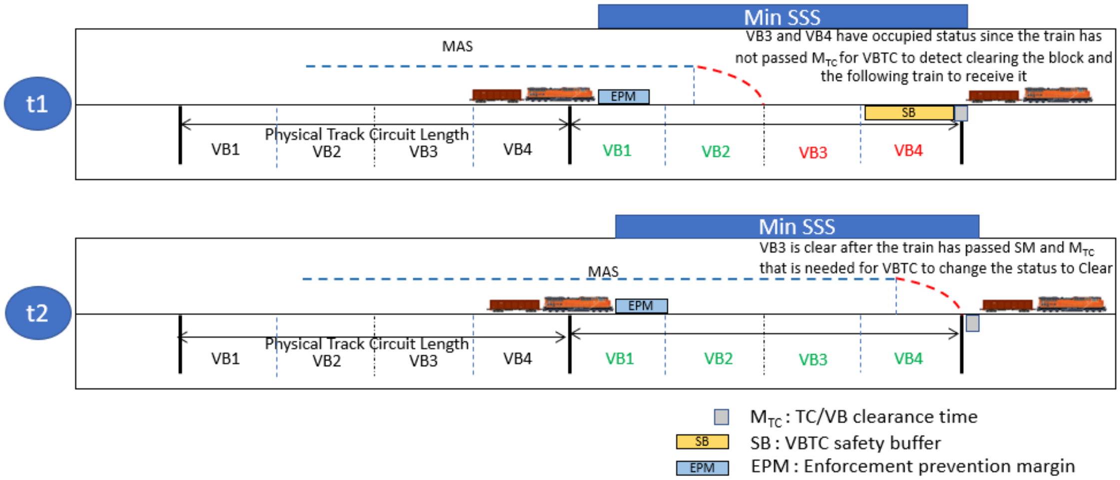


Figure 53. Train Speed Profile and Min SSS for VBTC when the Safety Buffer is Longer than the Braking Distance

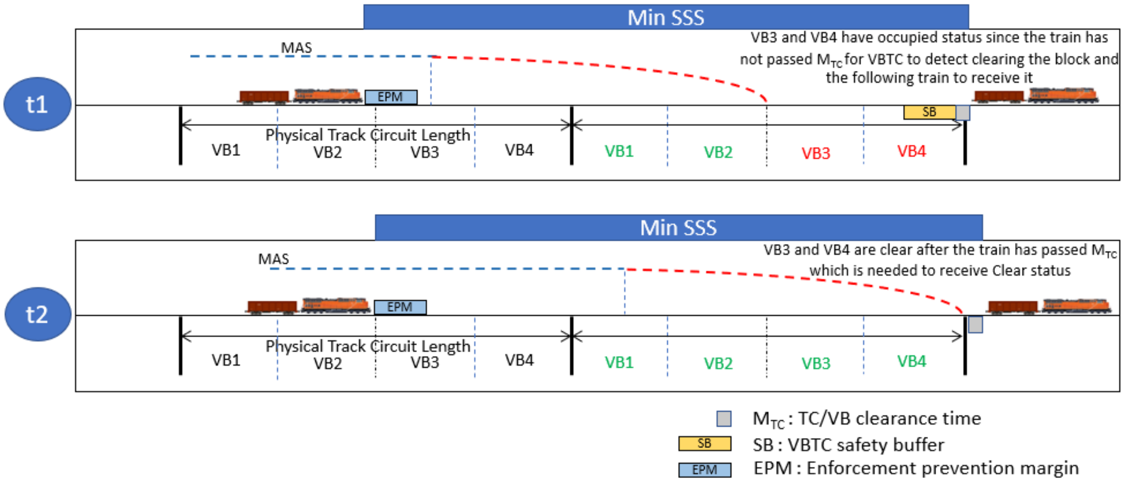


Figure 54. Min SSS for VBTC when the Braking Distance is Longer than the Safety Buffer

Min SSS$_{VBTC}$ is the minimum steady state separation between trains in EO-PTC operation with VBTC; BC$_0$ is the braking distance of the following train up to a full stop; SB is the safety margin for VBTC virtual blocks; M$_{TC}$ is the time required to convey that the track circuit or VB is Clear; and EPM is the enforcement prevention margin that allows the train engineer to act and avoid PTC enforcement. Min SSS$_{VBTC}$ is calculated based on the equations in (5), (6), and (7). When operating with VBTC under B-QMB, PTCEA roll-ups by a leading train must be sufficiently faster than the time it would take to traverse the distance of a virtual block plus the safety buffer. If PTCEA roll-ups are not fast enough, the Min SSS would be larger due to the PTCEA roll-up time when operating with VBTC. This case is not covered in this analysis, but it can easily be included in the Min SSS equations if further analysis is needed to support mainly QMB when operating with VBTC. However, the QMB system should be designed to roll-up PTCEAs fast enough to avoid this additional separation in most scenarios.

The margins for VBTC are given in (5) and (6) as follows:

- SB – Safety buffer distance that the end of train needs to pass from the previous VB boundary for VBTC to ensure the train is clear of the last VB (i.e., clear of the boundary)
- M_{TC} – Time required to convey to the following train that the track circuit (or VB in case of VBTC) is Clear, converted to distance (based on the leading train's speed)
- EPM – Enforcement Prevention Margin (in seconds) that is set between the warning time and the limit of predictive enforcement, assumed to be 20 seconds

$$\text{VBTC Min SSS } BC_{short} = (TC_L)/2 + SB + M_{TC} + EPM \quad \text{given } SB => BC_0 \tag{5}$$

$$\text{VBTC Min SSS } BC_{long} = (TC_L)/2 + BC_0 + M_{TC} + EPM \quad \text{given } SB < BC_0 \tag{6}$$

If $BC_0 \geq SB$

Then, Min SSS_{VBTC} = VBTC Min SSS BC_{long}

Else, Min SSS_{VBTC} = VBTC Min SSS BC_{short}

Figure 5 presents a proposed algorithm for Min SSS calculation when operating with VBTC. While this algorithm is used in this analysis to determine Min SSS, it can also form the basis of a pacing algorithm. A pacing algorithm directs a following train to adjust its speed or maintain the same speed. To achieve this, the VBTC Min SSS equations in (5) and (6) are calculated, as well as the inequality condition in (7). Next, the Min SSS_{VBTC} is determined based on the algorithm results according to the condition and equation values. If the braking distance of the train BC_0 is larger than the SB distance, then Min SSS_{VBTC} is equal to VBTC Min SSS BC_{long}. Otherwise, Min SSS_{VBTC} is equal to VBTC Min SSS BC_{short}.

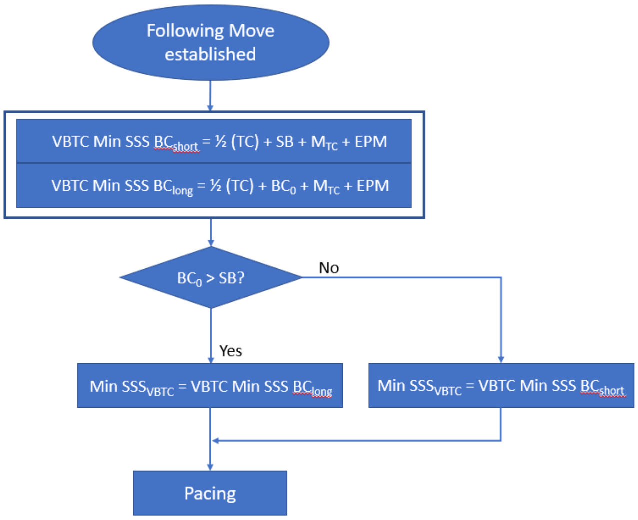


Figure 55. Flow diagram for an algorithm to calculate the Min SSS in following moves when using VBTC

3.1.4 Minimum SSS with FMB

FMB operation can be implemented using various methods and technologies. Regardless of the specific implementation method used, the separation between trains is based on the predicted braking distance of a following train in a following move operation plus margins added by the train control system, including the time required for rolling up and extending movement authorities (e.g., PTCEAs in QMB and FMB), delays or margins imposed by broken rail and rollout detection technologies, communication delays, processing delays, and train location uncertainties, including margins imposed by systems such as Vital Rear of Train Location (VRTL). The Min SSS for FMB, denoted by Min SSS_{FMB}, is given in (8), which consists of the following train's BC_0 plus a margin (QM) that includes multiple delays introduced by the system and a distance margin.

The margins in QM are given in (9), and include:

- $T_{roll\text{-}up}$ – Roll-up period (1/(roll-up rate)) in close following moves (nominally 16 sec)
- T_{PTCmsg} – PTC radio Superframe duration (in seconds)
- D_{SM} – Safety margin, which includes VRTL inaccuracy error and allowance for train stretching (in miles – usually given in feet but converted to miles in this equation)
- $T_{re\text{-}trans}$ – Average retransmission time of PTC messages that do not reach their destination (in seconds)
- T_{PhL} – Physical layer delays (in seconds), which include the communication backbone delay and processing delays of the on-board computers, back-office server, PTCEA manager, and radios

$$\text{Min } SSS_{FMB} = BC_0 + QM + EPM \tag{8}$$

$$QM = [(T_{roll\text{-}up} + T_{PTCmsg} + T_{re\text{-}trans} + T_{PhL}) * SL_{\text{-}trn}/3600] + DSM \tag{9}$$

3.2 Modeling Approach and Operational Scenarios

The research team developed an analytical model that calculates Min SSS for a pair of trains in following moves, limited to:

- Single track operation, uniform track circuit lengths
- Tracks without curvature on flat grade
- Three types of train (Loaded Freight, Expedited, and Passenger) with typical average deceleration rates
- Train separation calculated for a pair of trains operating at the same speed
- Analysis of operational scenarios for the following configuration (one per turn):
    - Three track circuit lengths: 1.2, 2.5, and 4.5 miles
    - Freight and Expedited trains operating at two different MAS: 49 and 60 mph
    - Passenger trains operating at two different MAS: 59 and 79 mph

Table 1 provides the deceleration rates with average train lengths used for each of the train types. These values are average numbers obtained from the analysis developed under other Federal

Railroad Administration (FRA)-funded projects (e.g., the HRCTC[1] and PTC RAM Phase 2[2] projects), where typical train consist configuration was provided by participant railroads. Expedited trains are mainly intermodal trains that have high priority commodities (a combination of higher brake ratios and less gross rail weight than typical freight trains allow intermodal trains to travel at higher speeds, hence the term "expedited trains").

Table 73. Train Deceleration Rates

	Freight	Passenger	Expedited
Deceleration Rate (mph/h)	1,000	4,000	3,500
Train Length (Mile)	1.42	0.19	1.41

The following assumptions were made, where applicable, for the calculation of Min SSS:

- There exists a pacing algorithm that allows a following train to maintain Min SSS. This algorithm requires knowledge of the approximate speed of a leading train so that a following train can match it.
- There exists an algorithm that determines when to activate the pacing algorithm on a following train.
- The track circuit length is known by the onboard, based on the track database.
- The onboard of a following train can detect when a leading train clears a double occupied block. This can be detected when the WSMs indicate that the virtual blocks ahead within the same physical block are unoccupied.
- M_{TC} is based on an average delay of 14 seconds, which is converted to distance in miles based on the speed of the leading train. Fourteen seconds is assumed to be the time to clear the physical block for conventional track circuits and to clear a VB in VBTC.
- The VBTC safety buffer is an average value of 1,500 feet.

Based on estimates, some assumptions for FMB (mainly QM) have been made for the margins, which include the following (refer to Appendix C-2 for further details):

- Safety margin is determined based on the VRTL inaccuracy error (which should be relatively small) plus an allowance for train stretching in certain scenarios. This analysis assumes ideal scenarios and conditions, and therefore, the safety margin is assumed to be zero.
- PTC Superframe messages (PTL-EOT 1x, leading train roll-up 1a, and PTCEA extension to the following train 2a) will have a 12-second delay (i.e., 4 seconds per PTC message for worst case scenario; see Appendix B for further details).
- Average retransmission delay is estimated to be 3.2 seconds, explained as follows:

---

[1] FRA Report No. DOT/FRA/ORD-22/30, Higher Reliability and Capacity Train Control

[2] FRA project "PTC Reliability, Availability, and Maintainability (RAM) Study Phase II" (Not yet published)

  - 6-second timeout for unreceived acknowledgement and waiting time
  - 0.75-second reprocessing time
  - 4 seconds for new PTC message
  - 0.1 seconds backbone communication delay
  - For three messages: 3*(6+0.75+4) + 2*(0.1) = 32.45 seconds
  - At a probability of 10 percent 1st try message loss, average retransmission delay= 32.45 sec * 0.1 = 3.2 sec
- Physical layer delay is 4.7 seconds. Physical layer delays includes 1) a backbone communication delay of 0.2 second (0.1 second for communication between the onboard of a leading train and BOS and 0.1 second for the communication between the BOS and the onboard of a following train) and 2) a processing delay of 4.5 seconds (0.75 second at each stage, i.e., VRTL, onboard of a leading train, FMB server roll-up processing, PTCEA parser, FMB server processing of new PTCEA, onboard of a following train); see Appendix B for more details.
- Roll-up rate of once every 16 seconds
  - This can be increased or decreased automatically (within configurable limits) by the PTCEA Roll-up Management Algorithm. A roll-up rate of once every 16 seconds is approximately what would be expected in a typical situation where Min SSS would apply, however, certain scenarios may benefit from a faster roll-up rate.

Therefore, a total of 35.9 seconds is added to the margin of the Min SSS distance in FMB.

3.3 Min SSS Comparison Results

Table 2 provides an example of Min SSS calculation without margins in EO-PTC with conventional track circuits and EO-PTC with VBTC for a given scenario. The results show that Min SSS in EO-PTC with conventional track circuits is around 1.4 times that of using VBTC with four virtual blocks, when margins are not included.

Table 74. Example of Min SSS Calculation (without Margins) for EO-PTC with Conventional Track Circuits and with VBTC that Has Four VBs

	Value	Unit
Deceleration braking rate	1000	mph/h
MAS	60	mph
VB size (1/4 Block)	0.625	miles
Block Length	2.5	miles
Braking distance to full stop (60 to 0)	1.80	miles
EO-PTC Min SSS conventional track circuits*	**4.30**	miles
EO-PTC Min SSS with VBTC**	**3.05**	miles

* Obtained using equation (4) without considering margins

** Obtained using equation (5) without considering margins

Table 3, Table 4, Table 5, Table 6, and Table 7 contain a detailed train separation assessment that takes into account the different margins of EO-PTC, EO-PTC with VBTC, and FMB operations. Table 3 presents a set of various scenarios of different train types, speeds, track circuits or block lengths, calculated margins, and braking distance to full stop for all train types at the different speeds. Table 4 provides the results for EO-PTC headway with conventional track circuits and EO-PTC with VBTC, and the proportional headway reduction percentage. Table 5 provides headway results for O-PTC, EO-PTC with conventional track circuits and with VBTC and makes a comparison between the results in terms of headway reduction percentage. Table 6 provides train headways calculated for O-PTC with three-aspect signaling, EO-PTC with conventional track circuits, and EO-PTC with VBTC. Finally, Table 7 provides the results of train headway for EO-PTC with half-length conventional track circuits and for FMB. Those are compared to EO-PTC with VBTC along with the corresponding headway reduction in percentages.

Table 75. Calculations of Braking Distances and Margins for Multiple Operational Scenarios

Train Type	MAS (MPH)	BC_0 (Mile)	TC_L (Mile)	M_{TC} (Mile)	SM (Mile)	QM (Mile)	EPM (Mile)
Freight	60	1.80	1.2	0.23	0.28	0.60	0.33
Expedited	60	0.51	1.2	0.23	0.28	0.60	0.33
Passenger	79	0.78	1.2	0.31	0.28	0.79	0.44
Freight	60	1.80	2.5	0.23	0.28	0.60	0.33
Expedited	60	0.51	2.5	0.23	0.28	0.60	0.33
Passenger	79	0.78	2.5	0.31	0.28	0.79	0.44
Freight	60	1.80	4.5	0.23	0.28	0.60	0.33
Expedited	60	0.51	4.5	0.23	0.28	0.60	0.33
Passenger	79	0.78	4.5	0.31	0.28	0.79	0.44
Freight	49	1.20	1.2	0.19	0.28	0.49	0.27
Expedited	49	0.34	1.2	0.19	0.28	0.49	0.27
Passenger	59	0.44	1.2	0.23	0.28	0.59	0.33
Freight	49	1.20	2.5	0.19	0.28	0.49	0.27
Expedited	49	0.34	2.5	0.19	0.28	0.49	0.27
Passenger	59	0.44	2.5	0.23	0.28	0.59	0.33
Freight	49	1.20	4.5	0.19	0.28	0.49	0.27
Expedited	49	0.34	4.5	0.19	0.28	0.49	0.27
Passenger	59	0.44	4.5	0.23	0.28	0.59	0.33

The results of train headways for EO-PTC when using conventional track circuits and when using VBTC are presented in Table 4. The Headway Reduction column shows the proportional reduction of headway in EO-PTC with VBTC compared to EO-PTC (i.e., headway reduction percentage when using VBTC instead of conventional track circuits when operating under EO-PTC). Train headway reduction for freight trains is in the range of 12 to 30 percent depending on MAS and track circuit lengths. For expedited and passenger trains, headway reduction is in the range of 16 to 34 percent and 20 to 40 percent, respectively.

Table 76. Headway Reduction for Various EO-PTC and EO-PTC with VBTC Scenarios

Train Type	MAS (mph)	TC_L (mile)	EO-PTC Headway* (mile)	EO-PTC with VBTC Headway† (mile)	Headway Reduction of EO-PTC with VBTC vs EO-PTC*† (%)
Freight	60	1.2	4.99	4.39	12.0%
Expedited	60	1.2	3.70	3.10	16.2%
Passenger	79	1.2	2.92	2.32	20.6%
Freight	60	2.5	6.29	5.04	19.9%
Expedited	60	2.5	5.00	3.75	25.0%
Passenger	79	2.5	4.22	2.97	29.6%
Freight	60	4.5	8.29	6.04	27.2%
Expedited	60	4.5	7.00	4.75	32.1%
Passenger	79	4.5	6.22	3.97	36.2%
Freight	49	1.2	4.28	3.68	14.0%
Expedited	49	1.2	3.43	2.83	17.5%
Passenger	59	1.2	2.39	1.79	25.2%
Freight	49	2.5	5.58	4.33	22.4%
Expedited	49	2.5	4.73	3.48	26.4%
Passenger	59	2.5	3.69	2.44	33.9%
Freight	49	4.5	7.58	5.33	29.7%
Expedited	49	4.5	6.73	4.48	33.5%
Passenger	59	4.5	5.69	3.44	39.6%

* The headway results for EO-PTC also apply to B-QMB

† The headway results for EO-PTC with VBTC also apply in most cases to B-QMB with VBTC

In Table 5, train headways are calculated for O-PTC with four-aspect signaling, EO-PTC with conventional track circuits, and EO-PTC with VBTC. The results show significant reduction in headways for following moves when implementing EO-PTC with conventional track circuits as compared to O-PTC with four-aspect signaling, with headway reduction varying from 13 to 51 percent for freight trains, 36 to 57 percent for expedited trains, and 39 to 61 percent for passenger trains. When comparing EO-PTC with VBTC to O-PTC with four-aspect signaling, the headway reduction was much higher and varied from 24 to 66 percent for freight trains, 46 to 71 percent for expedited trains, and 51 to 76 percent for passenger trains. It is unlikely that 4.5-mile track circuits/blocks are installed in areas where there is dense traffic. Therefore, the upper range of the results from capacity gain comparisons with O-PTC four-aspect signaling in this section may be higher than what is common in practical railroad operation. The last column includes the results acquired in Table 4 for headway reduction when implementing EO-PTC with VBTC compared to EO-PTC with conventional track circuits.

Table 77. Headway Reduction for Various O-PTC Four-Aspect Signaling, EO-PTC and EO-PTC with VBTC Scenarios

Train Type	MAS (mph)	TC$_L$ (mile)	O-PTC four-aspect Headway (mile)	EO-PTC Headway* (mile)	EO-PTC with VBTC Headway† (mile)	Headway Reduction of EO-PTC vs O-PTC* (%)	Headway Reduction of EO-PTC with VBTC vs O-PTC† (%)	Headway Reduction of EO-PTC with VBTC vs EO-PTC*† (%)
Freight	60	1.2	5.76	4.99	4.39	13.4%	23.8%	12.0%
Expedited	60	1.2	5.76	3.70	3.10	35.7%	46.2%	16.2%
Passenger	79	1.2	4.77	2.92	2.32	38.8%	51.3%	20.6%
Freight	60	2.5	9.66	6.29	5.04	34.9%	47.9%	19.9%
Expedited	60	2.5	9.66	5.00	3.75	48.2%	61.2%	25.0%
Passenger	79	2.5	8.67	4.22	2.97	51.3%	65.7%	29.6%
Freight	60	4.5	15.66	8.29	6.04	47.1%	61.4%	27.2%
Expedited	60	4.5	15.66	7.00	4.75	55.3%	69.7%	32.1%
Passenger	79	4.5	14.67	6.22	3.97	57.6%	72.9%	36.2%
Freight	49	1.2	5.62	4.28	3.68	23.8%	34.5%	14.0%
Expedited	49	1.2	5.62	3.43	2.83	39.1%	49.8%	17.5%
Passenger	59	1.2	4.52	2.39	1.79	47.2%	60.5%	25.2%
Freight	49	2.5	9.52	5.58	4.33	41.4%	54.5%	22.4%
Expedited	49	2.5	9.52	4.73	3.48	50.4%	63.5%	26.4%
Passenger	59	2.5	8.42	3.69	2.44	56.2%	71.1%	33.9%
Freight	49	4.5	15.52	7.58	5.33	51.2%	65.6%	29.7%
Expedited	49	4.5	15.52	6.73	4.48	56.7%	71.2%	33.5%
Passenger	59	4.5	14.42	5.69	3.44	60.6%	76.2%	39.6%

* The headway results for EO-PTC also apply to B-QMB

† The headway results for EO-PTC with VBTC also apply in most cases to B-QMB with VBTC

In Table 6, train headways are calculated for O-PTC with three-aspect signaling, EO-PTC with conventional track circuits, and EO-PTC with VBTC. The results show significant reduction in train headway for following moves when implementing EO-PTC with conventional track circuits compared to O-PTC with three-aspect signaling, with headway reduction varying from 13 to 31 percent for freight trains, 17 to 39 percent for expedited trains, and 16 to 42 percent for passenger trains. When comparing EO-PTC with VBTC to O-PTC with three-aspect signaling, headway reduction was much higher and varied from 15 to 51 percent for freight trains, 31 to 59 percent for expedited trains, and 33 to 65 percent for passenger trains. Calculations for O-PTC with three-aspect signaling is not applicable for freight trains with the 1.2-mile track circuit length scenario at speed of 60 mph since the braking distances of freight trains in this scenario are larger than the track circuit length. The last column includes the results acquired in Table 4 for capacity improvement when implementing EO-PTC with VBTC compared to EO-PTC. The results show that train headways in O-PTC with three-aspect signaling are smaller than those of four-aspect signaling.

Table 78. Headway Reduction for Various O-PTC Three-Aspect Signaling, EO-PTC and EO-PTC with VBTC Scenarios

Train Type	MAS (MPH)	TC_L (Mile)	O-PTC three-aspect Headway (Mile)	EO-PTC Headway* (Mile)	EO-PTC with VBTC Headway† (Mile)	Headway Reduction of EO-PTC vs O-PTC* (%)	Headway Reduction of EO-PTC with VBTC vs O-PTC† (%)	Headway Reduction of EO-PTC with VBTC vs EO-PTC*† (%)
Freight	60	1.2	N/A	4.99	4.39	N/A	N/A	12.0%
Expedited	60	1.2	4.47	3.70	3.10	17.3%	30.7%	16.2%
Passenger	79	1.2	3.45	2.92	2.32	15.5%	32.8%	20.6%
Freight	60	2.5	7.07	6.29	5.04	11.1%	28.8%	19.9%
Expedited	60	2.5	7.07	5.00	3.75	29.3%	47.0%	25.0%
Passenger	79	2.5	6.05	4.22	2.97	30.3%	50.9%	29.6%
Freight	60	4.5	11.07	8.29	6.04	25.2%	45.5%	27.2%
Expedited	60	4.5	11.07	7.00	4.75	36.8%	57.1%	32.1%
Passenger	79	4.5	10.05	6.22	3.97	38.1%	60.5%	36.2%
Freight	49	1.2	4.35	4.28	3.68	1.6%	15.4%	14.0%
Expedited	49	1.2	4.35	3.43	2.83	21.3%	35.1%	17.5%
Passenger	59	1.2	3.24	2.39	1.79	26.3%	44.8%	25.2%
Freight	49	2.5	6.95	5.58	4.33	19.7%	37.7%	22.4%
Expedited	49	2.5	6.95	4.73	3.48	32.0%	50.0%	26.4%
Passenger	59	2.5	5.84	3.69	2.44	36.8%	58.3%	33.9%
Freight	49	4.5	10.95	7.58	5.33	30.8%	51.3%	29.7%
Expedited	49	4.5	10.95	6.73	4.48	38.6%	59.1%	33.5%
Passenger	59	4.5	9.84	5.69	3.44	42.2%	65.1%	39.6%

* The headway results for EO-PTC also apply to B-QMB

† The headway results for EO-PTC with VBTC also apply in most cases to B-QMB with VBTC

Table 7 contains Capacity results for a comparison between EO-PTC with VBTC versus EO-PTC with half-length track circuits and between FMB versus EO-PTC with VBTC.

Table 79. Comparison of Train Headway Between EO-PTC with Half-length Track Circuits and EO-PTC with VBTC, and FMB versus EO-PTC with VBTC

Train Type	MAS (MPH)	TC_L (Mile)	EO-PTC Headway with half TC_L* (Mile)	EO-PTC with VBTC Headway† (Mile)	FMB Headway (Mile)	Headway Reduction of EO-PTC with VBTC vs EO-PTC with half TC_L*† (%)	Headway Reduction of FMB vs EO-PTC with VBTC† (%)
Freight	60	1.2	4.39	4.39	4.15	0%	5%
Expedited	60	1.2	3.10	3.10	2.87	0%	8%
Passenger	79	1.2	2.32	2.32	2.20	0%	5%
Freight	60	2.5	5.04	5.04	4.15	0%	18%
Expedited	60	2.5	3.75	3.75	2.87	0%	24%
Passenger	79	2.5	2.97	2.97	2.20	0%	26%
Freight	60	4.5	6.04	6.04	4.15	0%	31%
Expedited	60	4.5	4.75	4.75	2.87	0%	40%
Passenger	79	4.5	3.97	3.97	2.20	0%	45%
Freight	49	1.2	3.68	3.68	3.38	0%	8%
Expedited	49	1.2	2.83	2.83	2.53	0%	11%
Passenger	59	1.2	1.79	1.79	1.55	0%	13%
Freight	49	2.5	4.33	4.33	3.38	0%	22%
Expedited	49	2.5	3.48	3.48	2.53	0%	27%
Passenger	59	2.5	2.44	2.44	1.55	0%	37%
Freight	49	4.5	5.33	5.33	3.38	0%	37%
Expedited	49	4.5	4.48	4.48	2.53	0%	44%
Passenger	59	4.5	3.44	3.44	1.55	0%	55%

* The headway results for EO-PTC also apply to B-QMB

† The headway results for EO-PTC with VBTC also apply in most cases to B-QMB with VBTC

EO-PTC with VBTC showed similar performance with the same headways as those of EO-PTC with half-length track circuits in all scenarios.

Results for FMB capacity gains compared to EO-PTC with VBTC become more significant with larger track circuit lengths and/or with reduced train braking distance. Those headway reductions reach up to 37 percent for freight trains, up to 44 percent for expedited trains, and up to 55 percent for passenger trains.

The previously presented results indicate that there is great potential for increasing capacity with the use of VBTC when compared to the use of conventional track circuits. The results also indicate that FMB can provide additional capacity when compared to the use of VBTC.

Figure 6 and Figure 7 illustrate the Min SSS for freight trains with various track circuit lengths at MAS of 60 and 49 mph, respectively. The following can be observed from these results:

- FMB has constant lowest Min SSS values (unrelated to track circuit length)
- At shorter track circuit lengths, EO-PTC with half-length track circuits and EO-PTC with VBTC have results closer to FMB
- EO-PTC with half-length track circuits and EO-PTC with VBTC have similar results with equal headways (i.e., the two fitted lines for the headways are overlapping)
- Potential capacity gains (in terms of reduced headways) increase as track circuit length increases

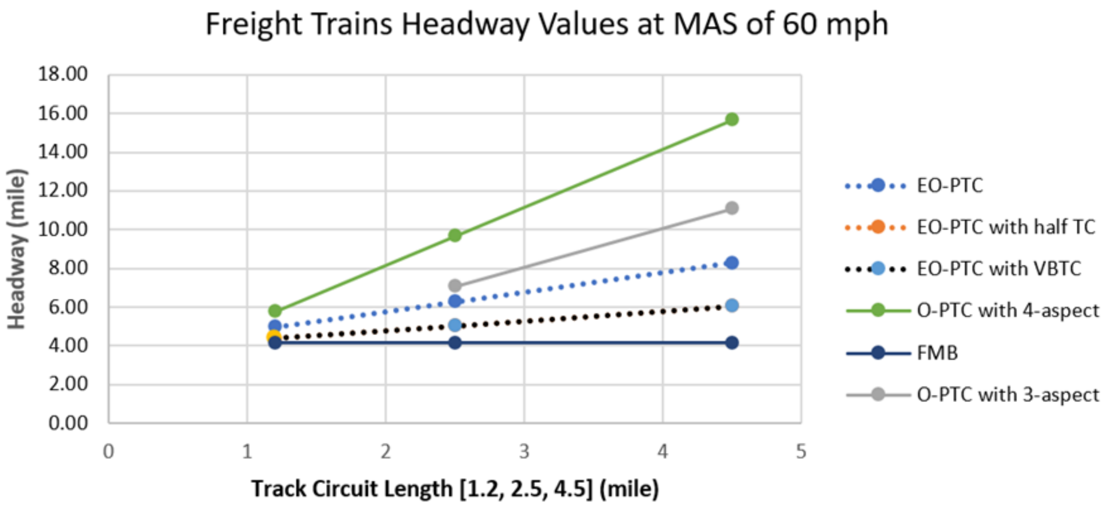


Figure 56. Min SSS for Freight Trains Operating at MAS of 60 mph

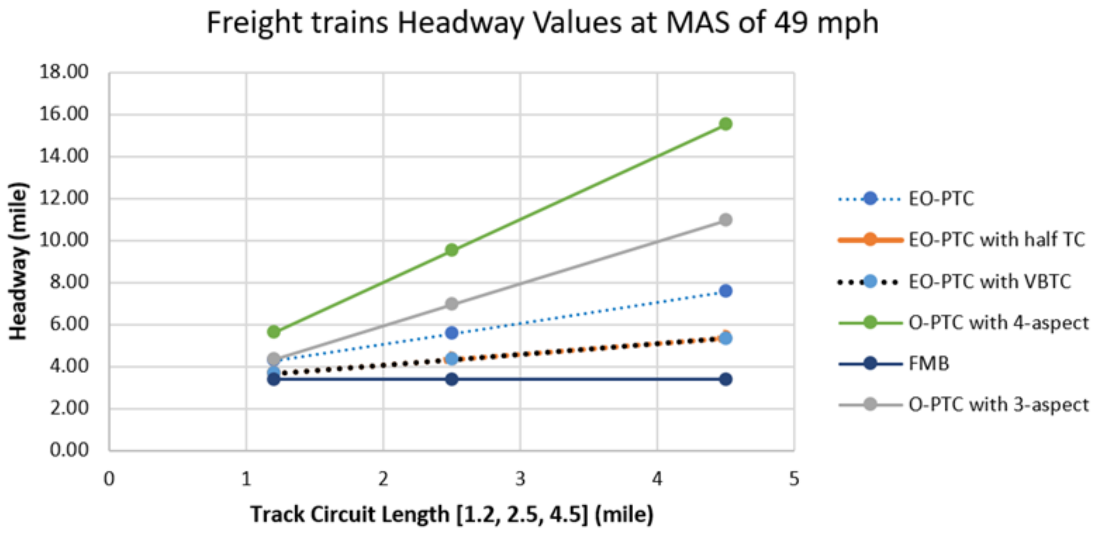


Figure 57. Min SSS for Freight Trains Operating at MAS of 49 mph

3.4 Assessment of Potential VBTC Enhancement Benefits

There is a limitation in the baseline (i.e., static) VBTC application code design on which this analysis is based. Each end of the track circuit reports two VB statuses on each side (i.e., the device at the right end of the track circuit reports VB3 and VB4 statuses of that physical block and VB1 and VB2 statuses of the next physical block, while the device at the left end reports statuses of VB1 and VB2 of that physical block and VB3 and VB4 of the previous physical block). The limitation of this application design lies in the inability of detecting and reporting a Clear status for the 3rd VB if there is an occupancy in the 4th VB. In certain scenarios, this could be considered as lost capacity (though minor) where headways could be slightly reduced if measures are taken to avert this limitation, as seen in Figure 8. Thus, additional capacity may be realized by making full use of VB statuses detected by both ends of a track circuit in VBTC, which could be achieved using different methods.

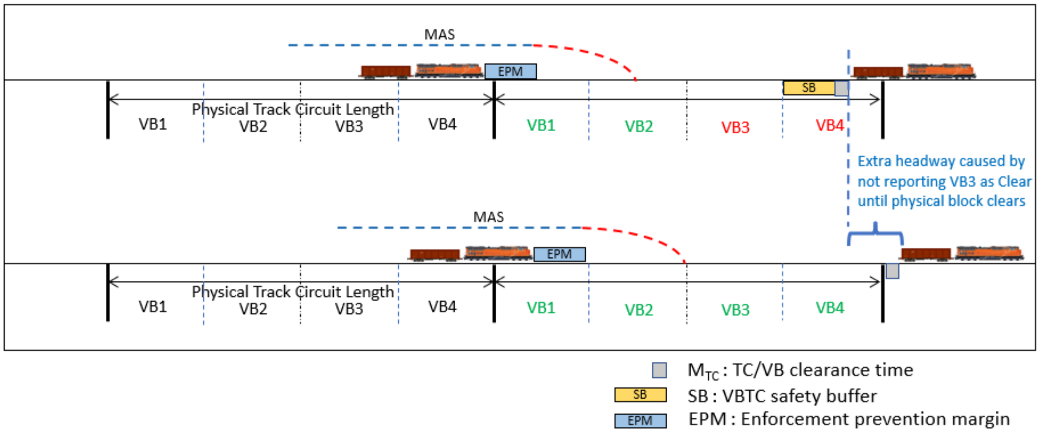


Figure 58. Extra Headway Caused by Not Detecting VB3 as Clear in the Example Baseline Application Code Design of VBTC

One method to address this is to use out-of-band communications (i.e., communications other than track codes) between VB wayside devices to report VB3 status (in situations where the 4th block is occupied) as Clear by the left end of the track circuit without overlapping VB statuses reported from both ends of the track circuit. This method would allow trains to operate with the reported VBTC statuses without any modifications to the onboard software. However, achieving reliable wayside peer-to-peer communication would add costs to a VBTC implementation for limited benefit.

Another method is to have both ends of a track circuit report all four VB statuses (a total of eight statuses for four VBs in one physical block) and use an algorithm in the onboard to reconcile the status of each VB. This algorithm could be simply an "OR" function that determines the status of a VB as Clear if any end of the track circuit reports it as Clear. This method would lead to straight-forward modifications to the onboard software. A similar solution not requiring a modification to the onboard software would be to transmit VB statuses in WSMs as Hazard Detection indications rather than Signal indications, since the ITC PTC onboard software is designed to reconcile the dual status reports for the same block from two different Wayside Interface Units (WIUs) in that case.

Another potential solution is implemented using an algorithm in the WIU software that reports only one status per each VB that is shown as Clear while not reporting any status for VBs that are not Clear in Outbound Movements. This way, the onboard will invoke a RSR for any VB that has unreported status. This method would not involve onboard software modifications and does not require wayside peer-to-peer communication but may require modifications to the WIU software or different VBTC application code to perform this function reliably. However, it is not clear if it is currently possible to devise an algorithm of that sort that works in all scenarios.

Furthermore, there is potential for increasing capacity further when VBTC is configured to operate with a higher number of VBs (with a requirement of first achieving the enhancement described earlier in this section, possibly by one of the three methods explained above). If that enhancement is implemented and a higher number of VBs are available in VBTC (e.g., eight VBs), Min SSS equations in this section would need to be modified to account for the new track circuit configuration to achieve minimum headways and obtain the desired capacity gains. Also, if a product is developed with smaller safety buffer ranges (if possible), this would also decrease train headways. It is not known at this time, however, whether either of these improvements in VBTC performance is achievable in a practical implementation.

4. Conclusion

The analysis indicates that significant reduction in train headway in following moves can potentially be obtained when using VBTC instead of conventional track circuits under EO-PTC operation in an ideal following move scenario. Train headway reduction for freight trains is in the range of 12 to 30 percent depending on MAS and track circuit lengths. For expedited and passenger trains, headway reduction is in the range of 16 to 34 percent and 20 to 40 percent, respectively. Multiple factors affect the results including track circuit length, train types with their corresponding real-time braking distance, MAS, and the SB distance for VBTC.

Reduction in train separation can lead to gains in overall network capacity, particularly in territories with a high train density operation in multiple track scenarios where all trains are moving in the same direction on the same track and can all achieve MAS, while all opposing train movements are on a different track. In most typical railroad operations, however, close following moves represent only a limited amount of railroad operations. Consequently, the potential capacity gains for following move scenarios estimated in the analysis are much higher than what can be expected in an actual railroad network scenario. Therefore, care must be taken to apply the results of this capacity analysis only to the specific scenarios in which they are applicable.

The analysis also shows similar train headway results between EO-PTC with VBTC and EO-PTC with half-length conventional track circuits. This indicates that doubling the track circuit lengths while replacing conventional track circuits with VBTC would not considerably impact capacity (depending upon the availability of VBTC being in VB mode and the availability of longer track circuits that can perform VBTC functionality). It also would eliminate around half the amount of track circuit equipment and IJs needed, which can result in savings in equipment and installation costs as well as savings in maintenance costs after installation.

The overall results indicate that implementing VBTC under EO-PTC has the potential to significantly reduce train separation and help increase railroad network capacity and efficiency in areas where capacity is being reached during following move operations. The results also indicate that FMB can provide even further capacity gains beyond that achievable with other train control methods operating in conjunction with VBTC.

Acronyms & Abbreviations

ACRONYM	**DEFINITION**
B-QMB	Basic Quasi Moving Block system
EO-PTC	Enhanced Overlay PTC
FMB	Full Moving Block system
MAS	Maximum Authorized Speed
Min SSS	Minimum Steady State Separation
O-PTC	Overlay PTC
PTC	Positive Train Control
PTCEA	PTC Exclusive Authority
PTL-EOT	Positive Train Location at End of Train
QMB	Quasi Moving Block system
RSR	Restricted Speed Restriction
SB	Safety Buffer – applied by VBTC
VB	Virtual Block
VBTC	Virtual Block Track Circuit
VRTL	Vital Rear-of-Train Location – synonymous with PTL-EOT
WIU	Wayside Interface Unit
WSM	Wayside Status Message

5. Reference Documents

Table 8 lists the documents used as a reference for this capacity analysis report. The VBTC Concept of Operations (ConOps) document is a companion to this capacity analysis. It is recommended that the ConOps be read before or in conjunction with this report. The capacity analysis highlights VBTC capacity benefits when implemented with O-PTC, EO-PTC, and QMB train control methods. Capacity comparisons that involve the FMB train control method are also discussed in this analysis. Therefore, the reader should have sufficient background about these train control methods that can be obtained by referring to the QMB ConOps, FMB ConOps documents, and more details about requirements of the system in the QMB/FMB System/Segment Requirements document. Documents listed below are available upon request from Jared Withers, FRA.

Table 80. Referenced Documents

VBTC Concept of Operations (Available upon request)
QMB Concept of Operation (Available upon request)
FMB Concept of Operation (Available upon request)
QMB/FMB System/Segment Requirements (Available upon request)
HRCTC project final report
PTC RAM Phase 2 project final report (In Review)

Appendix C-1. Main Concepts in QMB and FMB

Vital Rear-of-Train Location

Vital Rear-of-Train Location (VRTL) is a location determination system that provides dependable end-of-train (EOT) location information to a train’s locomotive, such as Positive Train Location End-of-Train (PTL-EOT) that is known as Next Generation Head-of-Train/End-of-Train (NGHE) or Gen 4 HE/EOT. VRTL is an optional technology that can complement O-PTC, EO-PTC, or QMB operations. However, VRTL is essential for achieving higher traffic capacity gains in advanced QMB or FMB operations.

Appendix C-2. Time Delays that Affect Margins in QMB and FMB

There are two distinct factors that must be considered in determining practically achievable minimum train separation in QMB and FMB. One is the safety margin required to be added to the end of a train's "cleared location" when reported in a roll-up message and the other is the collective effect of all other items that contribute to train separation. These other items just affect operations (i.e., minimum achievable headway). The delays for each category are as follows:

a. Rear-of-Train Location Uncertainty

The uncertainty of the location of the rear end of a train is dynamic, based primarily on the location error covariance as calculated by its VRTL system. Therefore, at the time of each PTCEA roll-up, the onboard obtains a high confidence estimate of the uncertainty (probably 6 or 7 sigma) for the current rear-of-train location report from VRTL. If there is any chance that the train was not fully stretched at the time of the report and that the train could have stretched further back beyond the reported location, then stretching margin also needs to be added. There are very few situations (if any) where this might occur, such as a train that stops while ascending a hill if/when the brake pipe air pressure is eventually depleted and hand brakes have not been set. The rear-of-train location uncertainty margin is applied by a train's onboard when determining the "From" limit to which it rolls up its PTCEA.

Note that if VRTL is not in use and the onboard uses its train consist information together with its front-of-train location to determine its rear-end location, there are several additional factors that need to be considered in determining the safety margin. These include front-of-train location uncertainty and train length uncertainty.

b. Track Circuit and Wayside Interface Unit (WIU) Response Time

This time delay, which is in the range of a few seconds, is primarily based on coded track circuit pulse rates. The WIU processing delays can be assumed to be insignificant in comparison. Track circuit delays affect Min SSS in O-PTC, EO-PTC, and QMB operations. Most potential FMB implementations do not use track circuits, or at least not in a way that affects Min SSS, so track circuit delays do not generally affect FMB operations. In the case of QMB, track circuit delays are in parallel with (not added to) the PTCEA thread-related delays. Consequently, Min SSS for the case of QMB is affected by whichever is the greater of track circuit-imposed train separation versus PTCEA-imposed train separation.

Track circuit delay comes into play at the moment a leading train clears a track circuit that had been jointly occupied with a following train up to that point in time (or a single occupancy clearance in the case of B-QMB or EO-PTC). The track circuit sends a pulse approximately every 3 seconds in the case of conventional track circuits (as a baseline case). It could be up to 3 seconds before the next pulse occurs to verify that the track circuit is clear ahead of the following train (since clearing an occupied block typically requires receiving two pulses). At this point, it will be necessary to wait until the PTC radio's F-frame timeslot occurs around again before this status change can be transmitted in a WSM. The F-frame timeslots occur on average. Based on the equipment used in this study, track circuits require the reception of 4 pulses (or may be designed to receive fewer pulses) before declaring a block to be Clear. The total delay would be 12 + 2 = 14 seconds. However, if the WSM was not heard by the locomotive, it will be another 4 seconds before the next WSM is transmitted.

There is no acknowledgment scheme on WSMs. Like item (d) below, it can be assumed that the WSM is not heard about one out of 10 times. This would add a re-transmission time of around 1 second on average to the delay. In O-PTC, additional time is needed to convey to the next block the status change to Clear of the previously occupied block in a cascading manner. This applies to one block in three-aspect signaling and two blocks for four-aspect signaling with around 5.2 seconds per block.

However, track circuit status does not affect PTCEAs, so track circuit delays are not additive to the other delays in QMB. Therefore, it needs to be determined which is the greater delay (track circuit plus WIU and radio response time or delays in the PTCEA update process) to determine minimum train separation. In most cases, PTCEA delays would be the larger number.

In this analysis, it is assumed that the time that a following train receives clearance of a virtual block is the same as that needed to receive clearance of a physical block, which is assumed to be 14 seconds.

c. PTC Radio Superframe Length

The PTC 220 MHz radio is designed with a 4-second Superframe size. When a short message (e.g., a WSM, PTCEA, or PTCEA Roll-up) is sent over the radio, it is sent in one time slot within the 4-second Superframe. On average, this results in 2 seconds of delay from the time a message is presented to the radio until it is transmitted. In a thread of messages where each message is in response to the receipt of a prior message in the thread and may include acknowledgements, there is an average of 4 seconds of radio-caused delay between sequential messages.

A “PTCEA update thread” is a thread of messages that affects train separation in QMB and FMB operations. The PTCEA update thread includes all the message transactions that must occur between the time a PTCEA roll-up is initiated by a rear-of-train location report at a leading train until the following train receives a PTCEA extension. The response to a message transmitted in one Superframe typically occurs in the subsequent Superframe (i.e., a 4-second delay is caused by the radio Superframe for each message transmitted in the thread). The following sequence of messages occurs during a PTCEA update thread:

1. VRTL on the leading train sends a rear-of-train location report to the front of the train using message 1x (in the case of a B-QMB leading train without VRTL, this step does not occur along with its associated delay)
2. Leading train (locomotive) sends a PTCEA Roll-up to the Office using message 1a
3. Office sends an updated PTCEA to the following train using message 2a

According to the current design for QMB and FMB systems, a total of 3 messages x 4 seconds = 12 seconds of delay in the PTCEA update process will occur in the PTC radio Superframe that directly adds to train separation in the case of QMB and FMB operations, if the total thread takes longer than the track circuit delays mentioned above.

d. Retransmission Time

Retransmission time is the delay added to message transmission when a radio message is not received on the first attempt (e.g., due to interference, fading, or insufficient signal level). When such an event occurs, the system has a mechanism to retransmit the message, in which the transmitter waits for an acknowledgement from the receiver and if the acknowledgment is not received within a certain amount of time, the transmitter resends the message. In this analysis, it was assumed that the acknowledgement is expected to be received in a subsequent Superframe (i.e., the next Superframe immediately after the initial transmission) and the retransmission is sent immediately after (i.e., in the next Superframe after the expected but unreceived acknowledgement).

This analysis also assumes that 10 percent of the PTC220 MHz radio messages fail (i.e., require retransmission). The PTCEA update thread includes 3 messages as cited in item PTC Radio Superframe Length, and retransmission time was accounted for in all cases. This is a time delay that directly and randomly affects train separation in situations where the PTCEA roll-up thread is the dominating factor in train separation.

e. Backbone Communications Delay

Field devices are linked to the office with a communication infrastructure that varies from one territory to another and among railroads. The communication infrastructure adds latency to the messages exchanged between the office and the field. Based on feedback obtained from participant railroads, the backbone delay was approximated at 0.1 second per each communication stage (i.e., communication delay between onboard of the leading train and the office, and between the office and onboard of the following train).

This is a time delay that directly affects train separation when the PTCEA thread dominates. This will vary from railroad to railroad. Most railroads have probably taken steps to keep this delay low to minimize impact on PTC.

f. Processing Delay

This is the time required for processing in the onboard computers and the office servers. It was assumed that in average each processing stage takes 0.75 seconds averaged at each stage:

- VRTL of leading train, to calculate rear-end position
- Onboard of the leading train to process rear-end position and roll-up its PTCEA
- Office, to process PTCEA Roll-up of the leading train
- Office, to update and parse PTCEAs
- Office, to create PTCEA extension of the following train
- Onboard of the following train to update its PTCEA

The six stages of processing in the PTCEA update process adds a total of 4.5 seconds of delay. This is a conservative estimate since processing time could be less especially with advanced capabilities in the Office computers. This is a time delay that directly affects train separation in cases when the PTCEA thread delay dominates.

g. Time Between PTCEA Roll-ups

When QMB trains are following each other at or near Min SSS, the update rate between PTCEA roll-ups (nominally 16 sec) can add to train separation. This is a time delay that directly affects train separation (unless the track circuit delays dominate).