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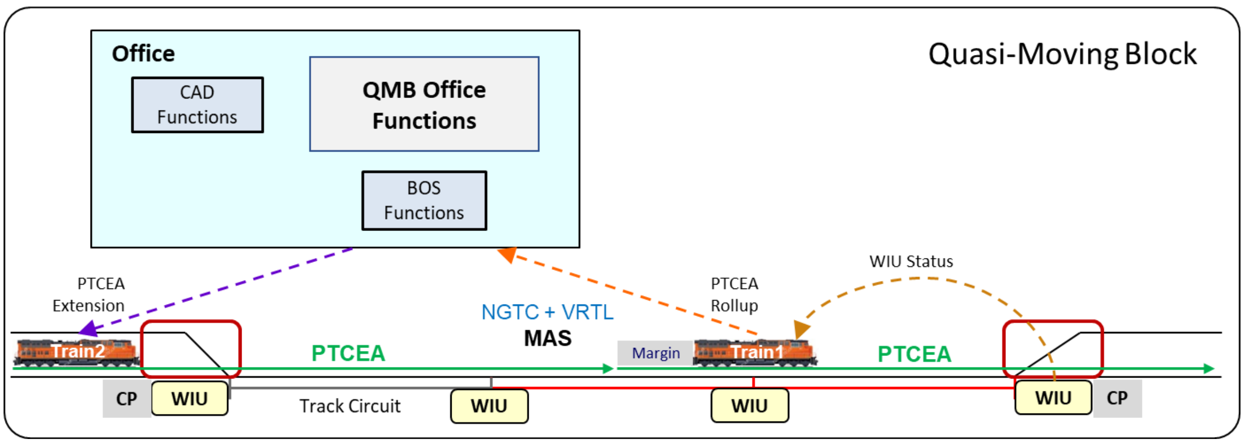
Broken Rail and Rollout Detection to Support QMB Operations



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14. ABSTRACT
Researchers collaborated with a railroad advisory group to demonstrate the validity of a track circuit concept that supports the Quasi-Moving Block (QMB) method of train control. They performed proof-of-concept testing, capacity analysis, hazard analysis, and requirements development.
QMB is one of three new additional modes of train control that have been identified as an evolution of today's Positive Train Control (PTC); namely, Enhanced Overlay PTC (EO-PTC), QMB, and Full Moving Block (FMB). QMB inherits the capacity benefits of EO-PTC and provides additional safety benefits compared to PTC. However, QMB remains limited by the fixed track circuit blocks and does not provide significant capacity benefits beyond EO-PTC unless supplemented by potential modifications to track circuits that, together with QMB and vital rear-of-train location, provide further capacity benefits.

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Positive Train Control, PTC, Quasi-Moving Block, QMB, next generation track circuit, NGTC, track circuit enhancements

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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

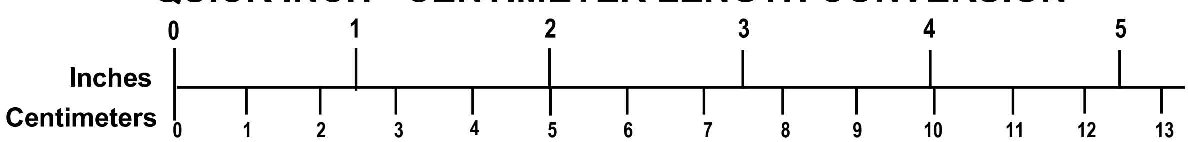
VOLUME (APPROXIMATE)

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)

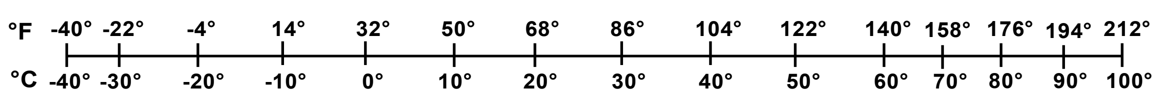
TEMPERATURE (EXACT)

[(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

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Executive Summary

Researchers collaborated with a railroad advisory group to demonstrate the validity of a next generation track circuit (NGTC) concept for broken rail and rollout detection that supports the Quasi-Moving Block (QMB) method of train control. They performed proof-of-concept testing, capacity analysis, hazard analysis, and requirements development from September 2019 through January 2021.

QMB is one of three new additional modes of train control identified as an evolution of today's Positive Train Control (PTC); namely, Enhanced Overlay PTC (EO-PTC), QMB, and Full-Moving Block (FMB). QMB inherits the capacity benefits of EO-PTC and provides additional safety benefits compared to PTC. However, QMB remains limited by the fixed track circuit blocks and does not provide significant capacity benefits beyond EO-PTC unless supplemented by potential modifications to track circuits that, together with QMB and vital rear-of-train location (VRTL), provide further capacity benefits.

To prove the NGTC concept, the research team demonstrated there was enough of a difference in the measured current when there was a rail break and when there was not. The smallest gap was created by the highest possible current level when a broken rail was present (i.e., broken rail at farthest end of track circuit), and the lowest possible current level when a broken rail was not present (i.e., unoccupied track circuit). Additionally, the team developed and validated an electrical model of the NGTC concept with test data.

Capacity analysis performed on the project further showed that QMB, with the NGTC concept plus VRTL, improved capacity in terms of the minimum steady-state separation. Train separation reduction varied from 20.36 percent to 45.89 percent among different train types. The analysis also showed comparable train separation results between QMB with NGTC and basic QMB with half-length track circuits.

An initial qualitative hazard analysis identified hazards and potential mitigations which were then reflected in the NGTC design and requirements. The analysis showed that only the rollout hazard group resulted in a notable, increased level of risk from current operations. However, this risk remained in the same risk category as conventional track circuits and overlay PTC. Hazards in this risk category can be acceptable with mitigation, through training, for example. As a result, the initial hazard analysis indicated there were no unacceptable hazards associated with the NGTC concept.

1. Introduction

This report describes continuing research and development on a track circuit method for broken rail and rollout detection intended to increase the network capacity benefits of Quasi-Moving Block (QMB) operations.

1.1 Background

A concept was previously developed to support future methods of train control, such as QMB or variants thereof, that is intended to be a simple, reliable, and cost-effective modification to existing track circuit technology. QMB is one of three new additional modes of train control that have been identified as an evolution of today's Interoperable Train Control (ITC) Positive Train Control (PTC):

1. **Enhanced Overlay PTC (EO-PTC)** consists of the realization of operational efficiency by not requiring nor enforcing speed restrictions related to Approach and Advance Approach indications when the PTC onboard is in the "active" state. Instead, speed reductions are based on braking distance to targets. This is a straightforward implementation that only requires reconfiguration of input tables of the Overlay PTC onboard system and changes to railroad operational rules.
2. **Quasi-Moving Block (QMB)** consists of governing any train operation in PTC territory by the issuance of non-overlapping movement authorities, known as PTC Exclusive Authorities (PTCEA). This offers more consistency in train control as well as safety improvements over current Overlay PTC, including the ability to provide rear-end collision protection and collision protection within a joint authority. QMB is a logical step in the migration to an FMB train control method that implements moving block to the extent possible while still relying upon fixed-block track circuits for detecting rail breaks and rollouts. As such, QMB can provide a portion of moving block capacity benefits in certain implementations.
3. **Full-Moving Block (FMB)** is a concept where track occupancy is determined by a train's footprint (from front 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 footprint to achieve near-theoretical maximum traffic capacity.

The Next Generation Track Circuit (NGTC) Concept of Operations (CONOPS) (Kindt, Brosseau, & Polivka, 2018) describes a broken rail detection method that allows a train, in a close following move in QMB territory, to enter an occupied block at higher speed without increased risk of encountering a broken rail, compared to operations in conventional Centralized Traffic Control (CTC)/Overlay Positive Train Control (O-PTC) territory.

Figure 1 provides an example of the current loop with the transmitted (Tx) signal. If the signal Tx is being transmitted and the current in the loop is substantial (i.e., $I \neq 0$), then the track circuit is clear of broken rails within that current loop. If the signal Tx is being transmitted and the current loop is near zero (i.e., $I = 0$), then there is a broken rail. Consequently, this method allows for the detection of broken rails, even with a shunting axle on the block, but does not distinguish if the track circuit is occupied or unoccupied if no further information is available.

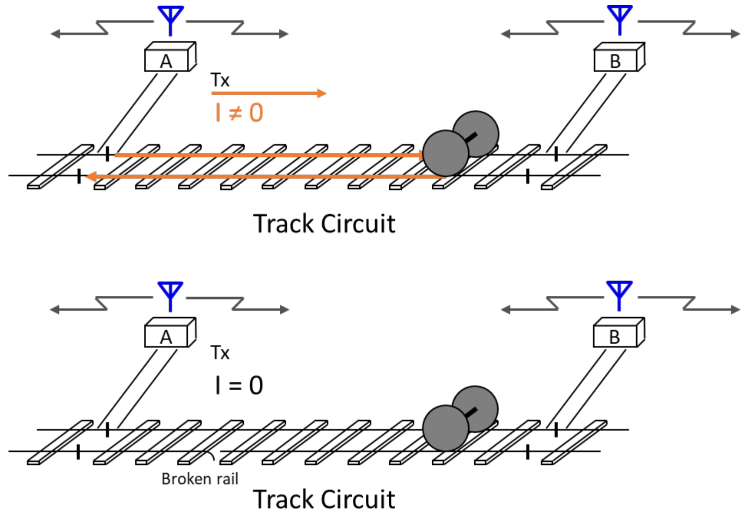


Figure 1. NGTC examples with Tx current

Figure 2 shows the QMB architecture with NGTC and vital rear-of-train location (VRTL). During a PTCEA roll-up, the leading train indicates it has operational VRTL within its message to the office. The office issues a PTCEA extension to the following train, explicitly stating that it can continue at maximum authorized speed (MAS) into an occupied block but is contingent on the train receiving valid wayside status messages (WSMs) confirming that NGTC is operational. Once the following train receives the NGTC-based WSM, it can then enter the occupied block at MAS and maintain MAS within the constraints of the PTC braking curve and PTCEA limit. After the following train enters the block, it is limited to restricted speed beyond the last end of train location reported by the leading train until the leading train clears the same block and no broken rails are detected.

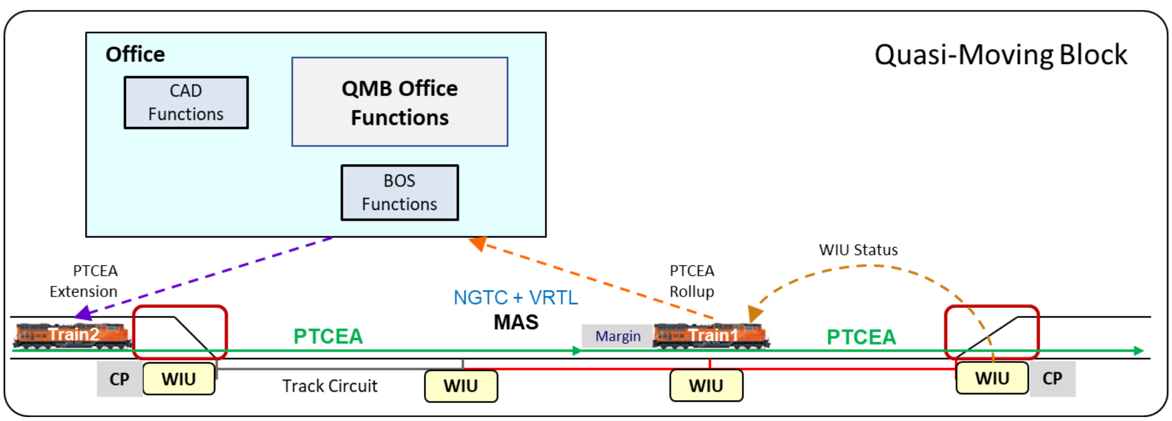


Figure 2. QMB architecture with NGTC + VRTL

1.2 Objectives

- Determine the extent to which electrical current can be used to reliably detect a broken rail (i.e., electrical open) with a shunting axle in the same track circuit under nominal circumstances.

- Identify technical challenges associated with fail-safe implementation of the conceptual design.
- Develop additional analyses and requirements documentation to advance the NGTC concept to support a possible future product development and evaluation phase.

1.3 Overall Approach

The project included collaboration with an Advisory Group (AG) made up of members from Class I railroads and the Federal Railroad Administration (FRA). They met to present the progress of the project, discuss and make decisions about project-related issues, and present and review results of technical analyses and testing. Project work included:

- Develop use cases, test cases, and test plan.
- Configure the Transportation Technology Center (TTC) testbed for testing.
- Perform static and dynamic testing.
- Analyze results.
- Conduct a capacity analysis.
- Conduct a hazard analysis.
- Develop a requirements specification.

1.4 Scope

Researchers configured the testbed and developed plans for proof-of-concept tests at TTC. The testing was not intended to comprehensively evaluate the technology, but rather to prove the concept under a variety of key use cases. Static and dynamic tests were conducted based on the test plans. Results of the tests were then analyzed to determine the reliability and physical limitations of the proposed NGTC concept. Efforts involving the development of a capacity benefit analysis, hazard analysis, and a requirement specification were included in the scope.

1.5 Organization of the Report

This summary report highlights the results of the project. The core output of the project is contained in the primary deliverables attached as appendices to this summary report. This report is organized as follows:

- Section 2 describes testing of the NGTC concept.
- Section 3 provides the capacity analysis with NGTC.
- Section 4 provides the NGTC hazard analysis.
- Section 5 describes the development of the NGTC requirements specification.
- Section 6 provides project conclusions and recommendations for next steps.
- Appendix A is the NGTC Capacity Analysis.
- Appendix B is the NGTC Hazard Analysis.
- Appendix C is the NGTC Requirements Specification.

2. NGTC Concept Testing

Researchers worked with an AG comprised of representatives from Class I railroads and FRA to develop and plan tests to explore the capabilities of the NGTC concept.

2.1 Test Approach

The research team developed test cases to determine if the NGTC concept was physically viable and to identify any limitations. The test cases were designed to compare the rail break detection performance of NGTC against that of conventional track circuits. The added functionality in which NGTC detects a broken rail in a block where a shunting axle is present should perform as well as broken rail detection for a conventional track circuit without a shunting axle.

The binary outcome (i.e., broken rail or not) for both NGTC and conventional track circuits is based upon making a comparison with a threshold value that accounts for practical considerations, such as current leakage through the ties and ballast. It is unknown what the threshold value is for conventional track circuits, and the threshold value for NGTC is a final design or implementation parameter that is left up to the supplier or railroad.

However, the viability of the NGTC concept can be evaluated by determining whether there is enough of a difference in the magnitude of the measured current level to clearly distinguish whether a rail break exists. The smallest gap in current levels is created by the highest possible current level with a broken rail and the lowest possible current level without a broken rail.

- **Highest possible current level with a broken rail** occurs when a rail break occurs at the farthest end of the track circuit, which captures the most amount of ballast conductivity.
- **Lowest possible current level without a broken rail** occurs when the track circuit is unoccupied.

2.2 Configuration of the TTC Testbed

The NGTC field testing was conducted on the Transit Test Track (TTT) at TTC. The TTT is a 9-mile loop that is divided into several signal blocks. Most blocks average 6,000 feet in length. All currently installed signal equipment was powered down and disconnected prior to the start of the NGTC testing. The NGTC test equipment was installed in the signal bungalows and connected to the welded signal track leads. The TTT is configured with a third rail intended for electrified testing. Because of this, each of the signal blocks has an impedance bond installed to allow for current return during electrified testing. Before NGTC testing began, all impedance bonds in the identified test section were disconnected to ensure there was no interference to the test results.

Figure 3 shows the TTT and the four different blocks, each 6,000 feet, used for the testbed. Two signal block lengths of 12,000 and 24,000 feet were established. The different sized signal blocks were configured by jumping around the insulated joints (IJs) at various locations by using the track signal wire in the signal bungalows. For the safety of test personnel and equipment, as well as test controllability, it was necessary to use electrically simulated rather than actual broken rails. This was done by two different methods: The first (and most often utilized) method was to disconnect the jumper wire at the determined rail joint location. This method created a complete electrical discontinuity. Another method was to add a resistor in parallel to the IJ, which simulated a partially broken rail or fully broken rail with some amount of physical contact.

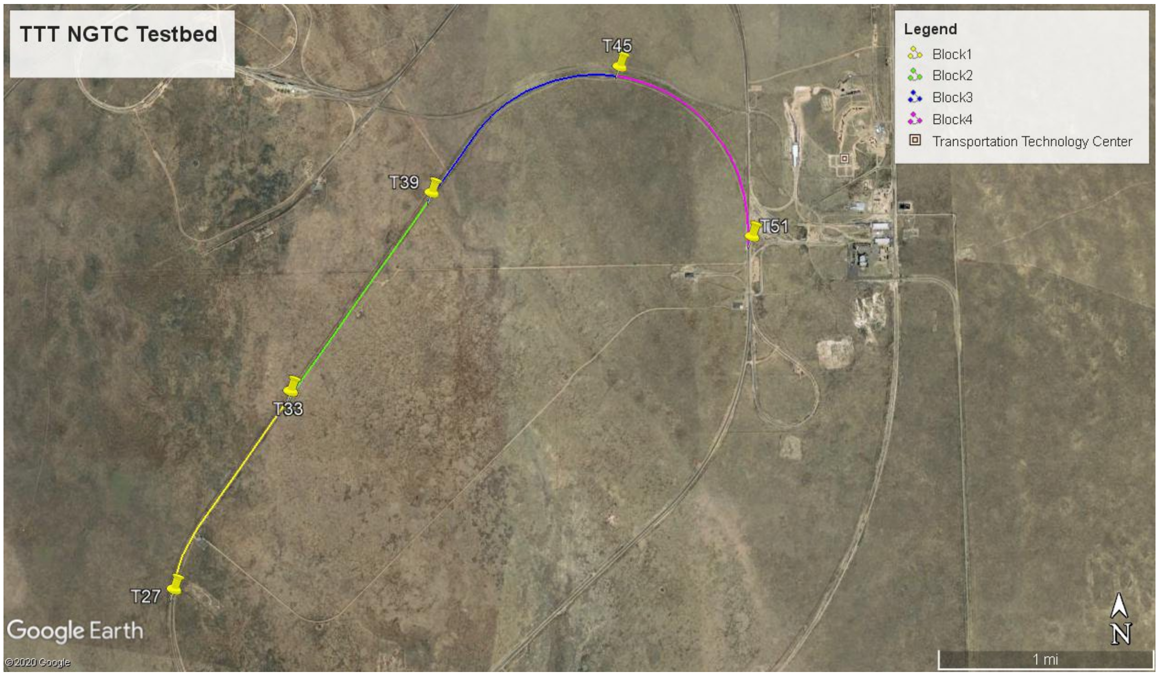


Figure 3. TTT testbed

A source-measuring unit (SMU) was used to supply DC voltage and to measure the electrical current (amp or A). The SMU was the Keithley 2460 (2400 Graphical Series SMU, n.d.). A LabVIEW program was developed to acquire data from the SMU.

An electrical diagram of the 12,000-foot testbed is seen in Figure 4. On the transmission side, the SMU applied a voltage to the rails and simultaneously measured the transmission current. The circuit included a 1-ohm, current-limiting resistor to reduce the current when a train was shunting near the SMU. On the opposite side of the block, the rails were electrically connected using a 2-ohm resistor to represent the relay. The relay resistor value conforms with the *American Railway Engineering Maintenance-of-Way Association Communication and Signals Manual* (AREMA C&S Manual) (Recommended Formulae for Computing Minimum Allowable Resistance Between Track Battery and Track and for Computing Related Current, 2012). The 24,000-foot testbed had four 6,000-foot blocks tied together.

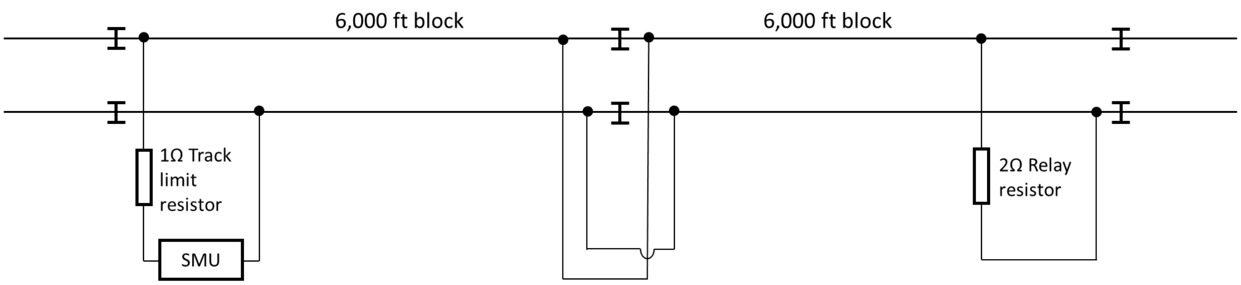


Figure 4. Electrical Diagram for 12,000-foot Signal Block

The team developed an electrical model to predict transmission current values to be observed while testing. As shown in Figure 5, the track circuit model included the resistance of the normal conductive path ($R_{NormPath}$) in parallel with ballast resistance ($R_{Ballast}$). The resistance $R_{NormPath}$ contained multiple series resistances, shown in Table 1. When the track circuit was unoccupied, the relay resistor was part of the normal conductive path and the shunting axle was absent. When the track was occupied, the shunting axle resistance was part of the normal conductive path and the relay resistor was ignored. Additionally, the model considered the distance of the shunting axle away from the SMU when calculating resistances for the normal conductive path and for the ballast.

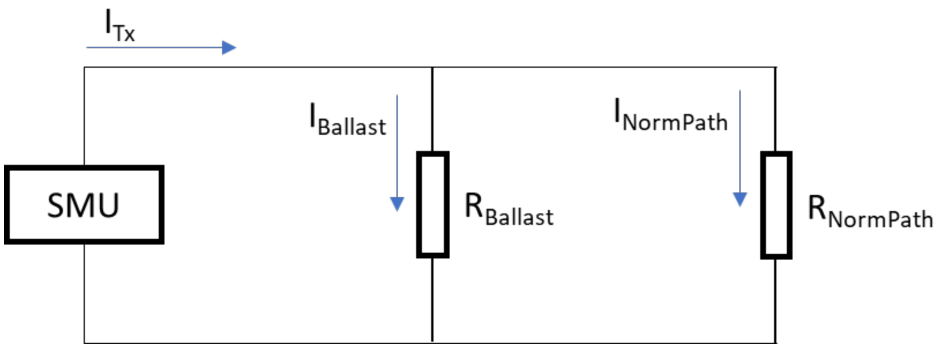


Figure 5. Simplified track circuit model

Table 1. Modeled resistance of normal conductive path for testbed

	12,000-foot Testbed	**24,000-foot Testbed**
Distributed rail resistance, where d = distance in ft.	R(d) ≈ (0.02 Ω/1,000 ft.) * d R(12,000 ft.) = 0.24 Ω	R(d) ≈ (0.02 Ω/1,000 ft.) * d R(24,000 ft.) = 0.48 Ω
Track cables	R(T51) = 0.1 Ω R(T45) = 0.2 Ω R(T39) = 0.1 Ω	R(T51) = 0.1 Ω R(T45) = 0.2 Ω R(T39) = 0.2 Ω R(T33) = 0.2 Ω R(T27) = 0.1 Ω
Track limit resistor	R(T51) = 1 Ω	R(T51) = 1 Ω
Relay resistor	R(T27) = 2 Ω	R(T27) = 2 Ω
Shunting axle	R = 0.06 Ω	R = 0.06 Ω
Unoccupied resistance (without shunting axle)	**3.64 Ω**	**4.28 Ω**

The voltage for the SMU was experimentally determined. Various voltages were applied while the transmission current was measured. An applied voltage of 2V was selected for both 12,000-foot and 24,000-foot blocks because the nominal transmission current was in line with conventional track circuits.

Table 2 lists the electrical values as utilized and measured for the unoccupied track. Resistance was calculated using the measured values and therefore represents the overall resistance of the testbed. Since the calculated resistance was close to the predicted resistance $R_{NormPath}$, the ballast resistance was very high for the testbed.

Table 2. Electrical values for unoccupied track circuit

Track Circuit Length	Selected Voltage	Measured Transmission Current	Calculated Resistance Based on Measured Values ($R = V / I_{Tx}$)	Predicted Resistance ($R_{NormPath}$)
12,000 ft.	2 V	0.55 A	3.63 Ω	3.64 Ω
24,000 ft.	2 V	0.5 A	4 Ω	4.28 Ω

2.3 Results

Static and dynamic tests were conducted using the testbed configured as previously described. For static tests, the shunt was created by an empty railcar to provide realistic shunting. A locomotive placed the empty railcar into position, then the locomotive decoupled from the railcar and exited the block. For dynamic tests, occupancy types involved a single four-axle locomotive, a train with multiple freight cars, and a hi-rail vehicle. The multiple-car train consist was assembled with a locomotive, one empty railcar, nine loaded railcars, and one tank car with water. Testing included movements in either direction running at multiple speeds. All data was logged and stored for post-test analysis.

For all tests, the applied voltage was 2V and the transmission current (I_{Tx}) was measured. In some test cases, the current at the end of the block opposite the SMU was also measured by adding an ammeter in series with the relay resistor. However, adding the ammeter in series on the relay side did cause some temporal anomalies with the measured transmission current during the dynamic tests. These anomalies were discovered during the dynamic tests for the 12,000-foot block. It was deemed unnecessary to repeat the dynamic tests for the 12,000-foot block because there was sufficient data acquired for the 24,000-foot block.

The maximum speed that could be maintained for the multiple-car train consist was empirically determined to be about 20 mph due to the incline of the track. Consequently, data was recorded at 20 mph for the single four-axle locomotive and the hi-rail vehicle.

Results for the static tests are presented in Table 3 and Table 4 for the 12,000-foot and 24,000-foot testbeds, respectively. Results for the dynamic tests are found in Table 5.

Table 3. Results for static tests with 12,000-foot block

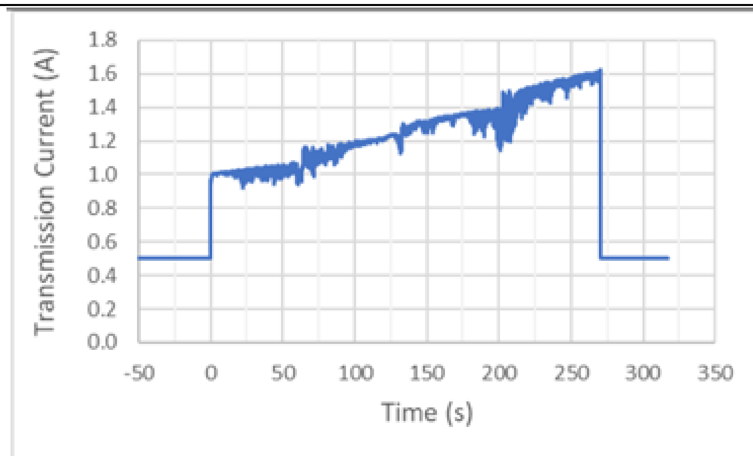
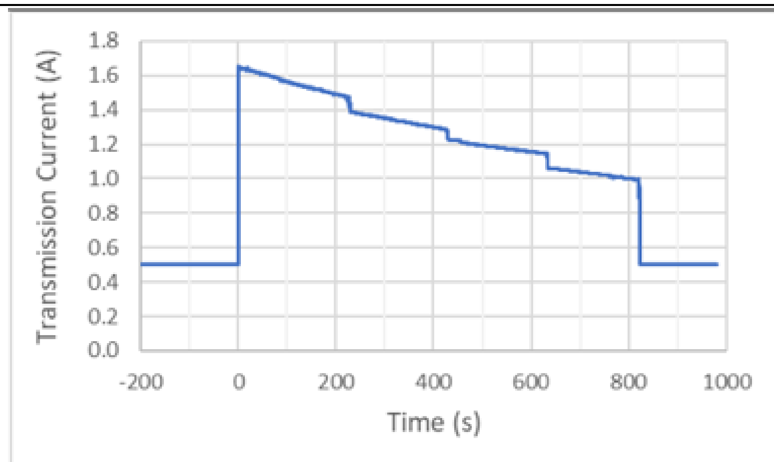
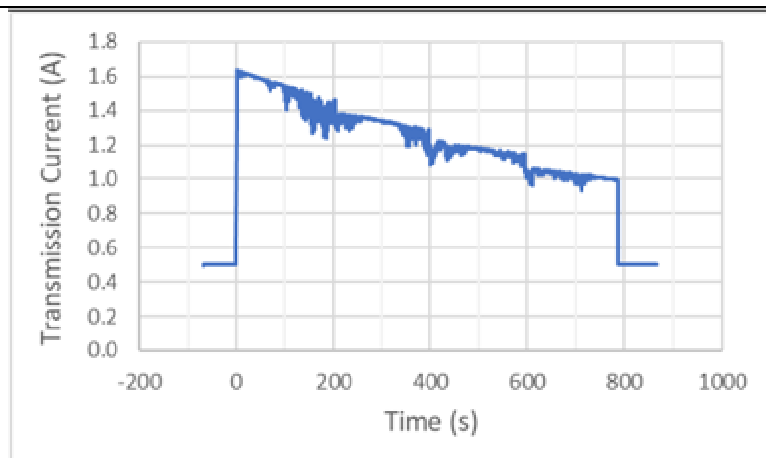
Static	Break Location	Occupancy Location	Type of Occupancy	Average Measured Current I_{Tx}
Clear track	N/A	N/A	N/A	0.55 A
Occupied without Break	N/A	Near V source	Empty car	1.72 A
	N/A	Mid-block	Empty car	1.4 A
	N/A	Far end from V source	Empty car	1.31 A
Unoccupied with Break	Near V source	N/A	N/A	Noise near 0
	Mid-block (short)	N/A	N/A	0.55 A

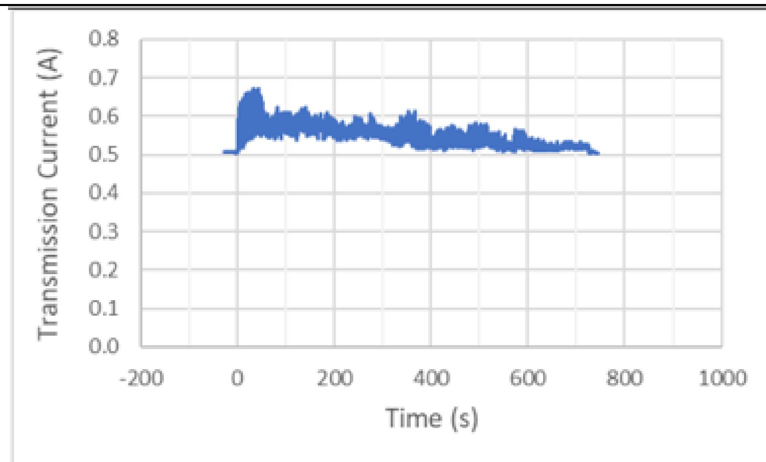
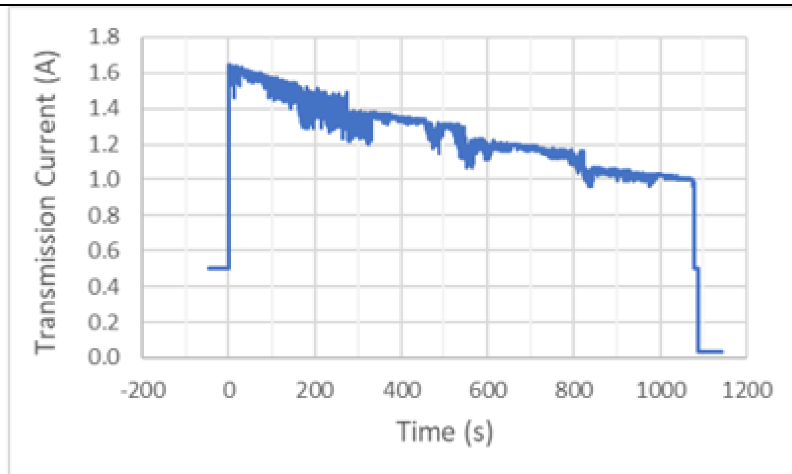
Static	Break Location	Occupancy Location	Type of Occupancy	Average Measured Current I_{Tx}
	Mid-block (1 Ω)	N/A	N/A	0.43 A
	Mid-block (10 Ω)	N/A	N/A	0.15 A
	Mid-block (100 Ω)	N/A	N/A	20 mA
	Mid-block (1 kΩ)	N/A	N/A	3 mA
	Mid-block (open)	N/A	N/A	Noise near 0
	Far end from V source	N/A	N/A	Noise near 0
Occupied with Break	Between V source & occupancy	Near V source	Empty car	Noise near 0
	Near V source	Mid-block	Empty car	Noise near 0
	Near occupancy (source side) (short)	Mid-block	Empty car	1.37 A
	Near occupancy (source side) (1 Ω)	Mid-block	Empty car	0.82 A
	Near occupancy (source side) (10 Ω)	Mid-block	Empty car	0.18 A
	Near occupancy (source side) (100 Ω)	Mid-block	Empty car	21 mA
	Near occupancy (source side) (1 kΩ)	Mid-block	Empty car	Noise near 0
	Near occupancy (source side) (open)	Mid-block	Empty car	Noise near 0
	Near V source	Far end from V source	Empty car	Noise near 0
	Mid-block	Far end from V source	Empty car	Noise near 0
	Between far end & occupancy	Far end from V source	Empty car	1.31 A

Table 4. Results for static tests with 24,000-foot block

Static	Break Location	Occupancy Location	Type of Occupancy	Average Measured Current I_{Tx}
Occupied without Break	N/A	Near V source	Empty car	1.64 A
	N/A	Mid-block	Empty car	1.25 A
	N/A	Far end from V source	Empty car	0.99 A
Occupied with Break	Near V source	Near V source	Empty car	Noise near zero
	Mid-block	Mid-block	Empty car	~3 mA
	Far end from V source	Far end from V source	Empty car	0.99 A

Table 5. Results for dynamic tests with 24,000-foot block

Test Conditions	Graph of Results
Single four-axle locomotive, no break, 60 mph	
Multiple-car consist, no break, 20 mph	
Single four-axle locomotive, no break, 20 mph	

Test Conditions	Graph of Results
Hi-rail, no break, 20 mph	
Single four-axle locomotive, break behind train at end of block, 15 mph	

2.4 Analysis of Results

Following the objectives of the test plan, researchers evaluated the results to determine if the NGTC concept was viable at the physical level and to identify any limitations. Additionally, the electrical model seen in Figure 5 provides a representation of what happens in an actual track circuit. The advantage of the electrical model is the ability to easily perform a parametric study and push the limits beyond what can be done on a testbed. Selectable model inputs for parametric studies included voltage, track length, resistances, and additive Gaussian noise. Outputs of the model included:

- Transmission current versus distance of shunt from the Tx side
- The gap between high and low detectable signal levels

To complete the model, a numerical value for the ballast resistance was needed. The ballast resistance was measured with an ohmmeter, without any connection between the rails, and at selected lengths that were defined by the distance between insulated joints. Table 6 provides the measured ballast resistance under various conditions. The ballast resistance was then calculated in terms of Ω-kft. This quantity was useful as the ballast resistance could then be estimated by dividing by any given length of track. The longer the track circuit length, the smaller the ballast impedance.

Table 6. Measured ballast resistance

Track Condition	Length (feet)	Measured Resistance (Ω)	Ω-kft
Dry	6,000	29,000	174,000
Dry	12,000	7,900	94,800
Snow	6,000	600	3,600
Melted snow	6,000	234	1,404

There was some discrepancy for the normalized dry ballast with lengths of 6,000 and 12,000 feet. One possible explanation is that the nominal ballast conductivity could have been greater overall (i.e., lower resistance) for the 12,000-foot block. A nominal ballast resistance of 100,000 Ω-kft was estimated for dry conditions and was used for the model.

Figure 6 provides the results of the model in terms of transmission current versus distance of shunt from the Tx SMU. The model was established such that a single shunt of 0.06 Ω proceeded along the track and was clear at/before 0 feet and at or after 24,000 feet. "Ideal" represents a normal track circuit with only the distributed rail resistance, R(d). "Actual" represents the 24,000-foot testbed and includes the discrete resistances at 6,000, 12,000, and 18,000 feet due to track cables at insulated joint locations. These discrete resistances caused slight drops in transmission current after the axle crossed them, and the track cable resistance was added into the normal conductive path.

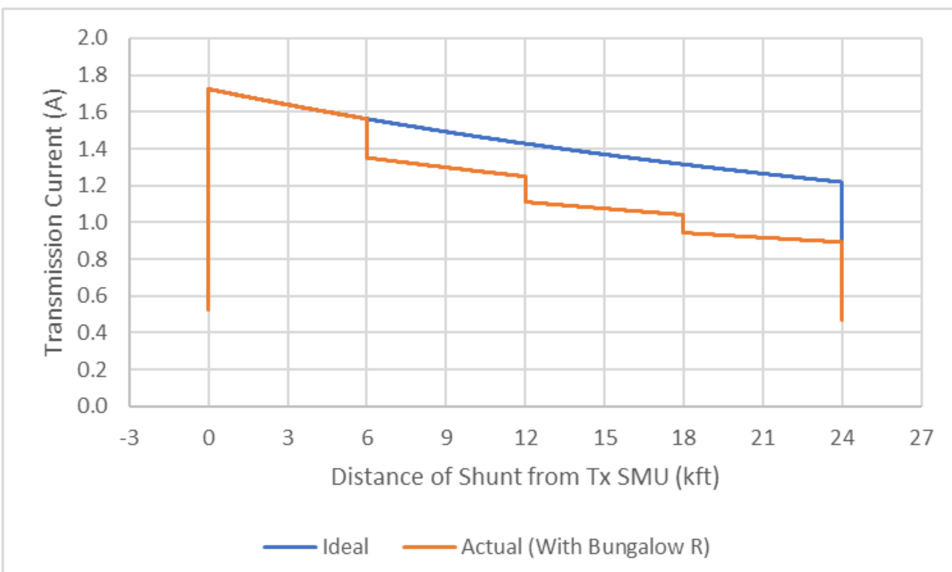


Figure 6. Electrical model for 24,000-foot testbed

The model was validated with test data (see Figure 7). The figure is presented in terms of transmission current versus distance of shunt from the Tx SMU. For the test data, a multiple-car train consist was moving away from the SMU at 20 mph. The test data was converted from time to distance so that it could be compared with the model.

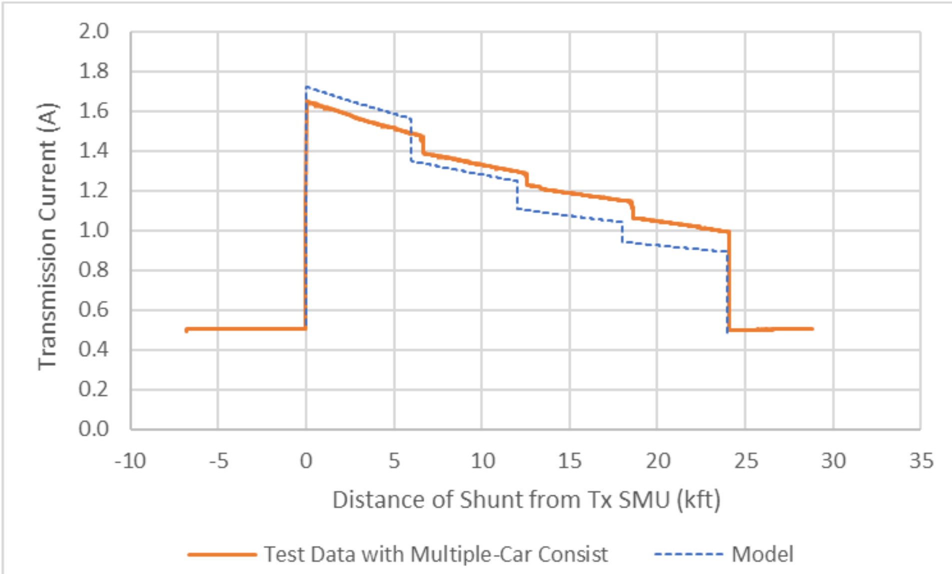


Figure 7. Test data and electrical model for 24,000-foot testbed

One of the dynamic tests is of particular relevance for evaluating the proof-of-concept condition with the smallest signal gap between high and low signals. In this test, a single four-axle locomotive moved away from the transmission side of the block and a broken rail was simulated after the train passed. The broken rail was located at the farthest distance away from the transmission side at 24,000 feet. Thus, extreme conditions were established – lower shunting with the four-axle locomotive, and a broken rail 24,000 feet away. Figure 8 presents the result of the entire dynamic test, and Figure 9 zooms in on the same result between 1,000 and 1,160 seconds.

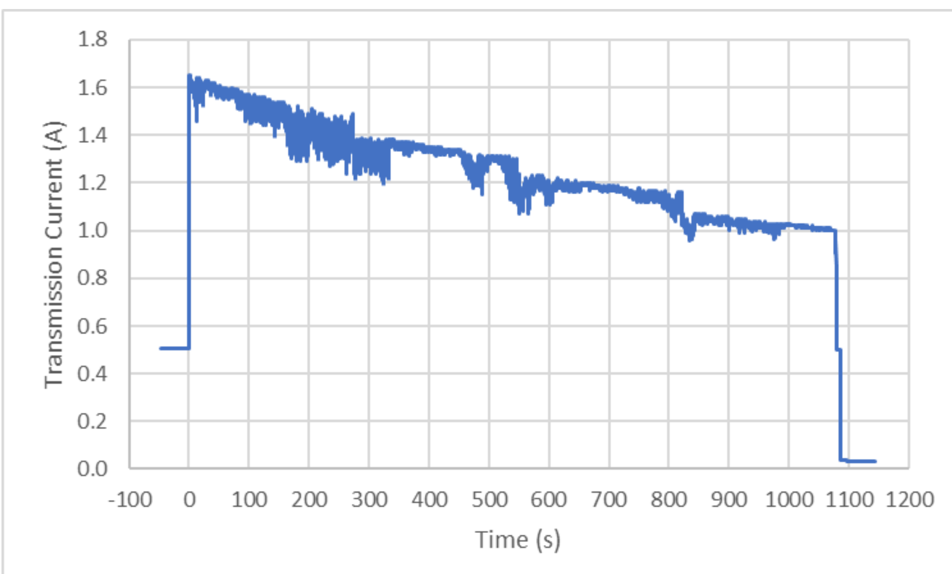


Figure 8. Single, four-axle locomotive moving from T51 to T27 at 15 mph

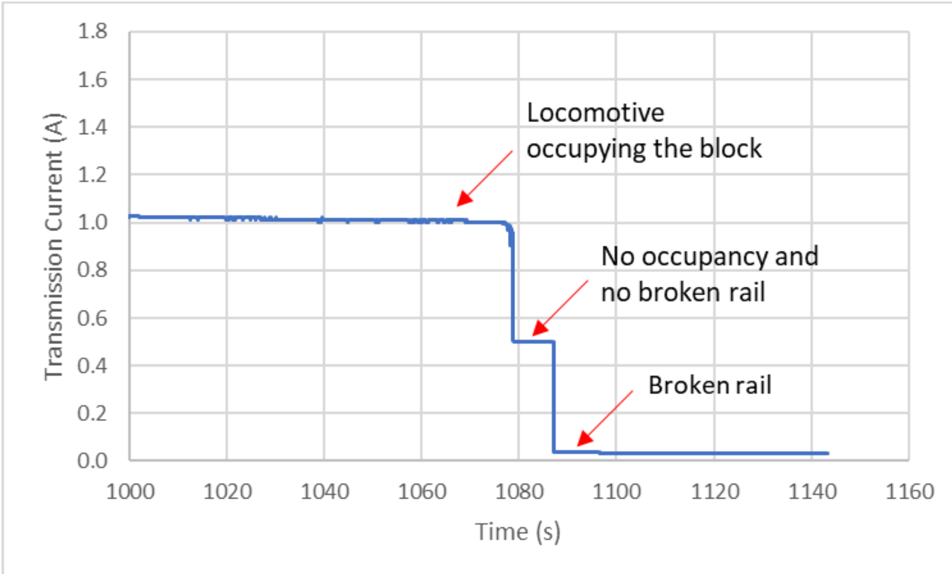


Figure 9. Single, four-axle locomotive moving from T51 to T27 at 15 mph, demonstrating the concept

Looking closer at Figure 9, the gap between the signals with and without a broken rail present can be observed. The locomotive was occupying the block until it exited at about 1,080 seconds. Upon the locomotive exiting the block, the 2Ω relay resistance was in the normal conductive path and lowered the transmission current to about 0.5A. This value of 0.5A was the lowest possible current level without a rail break under the selected conditions and was created by the unoccupied track circuit. Consequently, the proof-of-concept did not actually need to include a shunting axle, but the moving locomotive was used for illustrative purposes and to fully present the transmission current data. A wire was then disconnected at T27, which simulated a broken rail 24,000 feet away from the transmission side of the block. This near-zero value was the highest possible current level with a broken rail because it included all possible current in the ballast. Therefore, the smallest gap between the current level with a broken rail and the current level without a broken rail was about 0.5A for the selected conditions.

The gap between the current level with a broken rail and the current level without a broken rail can be further analyzed by using the track circuit model in Figure 5. Using Kirchhoff's current law for the highest possible current level with a broken rail (denoted "L") and lowest possible current level without a broken rail (denoted "H") signals:

$$I_{Tx\_L} = I_{Ballast\_L} + I_{NormPath\_L} = \frac{V}{R_{Ballast\_L}} + \frac{V}{R_{NormPath\_L}} \tag{1}$$

$$I_{Tx\_H} = I_{Ballast\_H} + I_{NormPath\_H} = \frac{V}{R_{Ballast\_H}} + \frac{V}{R_{NormPath\_H}} \tag{2}$$

The gap between these signals is:

$$I_{Gap} = I_{Tx\_H} - I_{Tx\_L} \tag{3}$$

$$I_{Gap} = \left(\frac{V}{R_{Ballast\_H}} + \frac{V}{R_{NormPath\_H}}\right) - \left(\frac{V}{R_{Ballast\_L}} + \frac{V}{R_{NormPath\_L}}\right) \tag{4}$$

It is assumed that the steady-state ballast resistance does not change whether or not there is a rail break:

$$R_{Ballast} = R_{Ballast\_H} = R_{Ballast\_L}$$

Therefore,

$$I_{Gap} = \frac{V}{R_{NormPath\_H}} - \frac{V}{R_{NormPath\_L}} \tag{5}$$

The resistance of the normal conductive path is approximated as $R_{NormPath\_L} \rightarrow \infty$ for a rail break:

$$\frac{V}{R_{NormPath\_L}} = 0$$

Therefore,

$$I_{Gap} = \frac{V}{R_{NormPath\_H}} \tag{6}$$

This result indicates that the gap between the current level with a broken rail and the current level without a broken rail will increase with:

- Larger applied voltage, or
- Smaller resistance of the normal conductive path.

Consequently, even though the signals with and without a broken rail present are individually impacted by the ballast resistance, the gap between them is the same, even with varying ballast conditions.

Table 7 presents the results for static tests with variable broken rail resistance for the 12,000-foot testbed. The broken rail was simulated by adding an extraneous path resistor in parallel with an IJ at T45. Tested values for the parallel resistor included a short (i.e., no broken rail), 1 Ω, 10 Ω, 100 Ω, and 1 kΩ. The trend was such that with higher extraneous path resistance, the smaller the measured current.

The measured current with the broken rail I_{Tx_L} and I_{Gap} can be calculated with respect to the current level without a broken rail I_{Tx_H}, which was about 0.55A.

Table 7. Broken rail with variable resistance for 12,000-foot testbed

Extraneous Path Resistor	**Measured Current (I_{Tx_L})**	**$I_{Gap} = I_{Tx\_H} - I_{Tx\_L}$**
0 (short)	0.55 A	0
1 Ω	0.43 A	0.12 A
10 Ω	0.15 A	0.40 A

Extraneous Path Resistor	Measured Current (I_{Tx_L})	$I_{Gap} = I_{Tx\_H} - I_{Tx\_L}$
100 Ω	20 mA	0.53 A
1 kΩ	3 mA	0.55 A

Impacts of the extraneous path resistance can be analytically determined. With the extraneous path resistor, the resistance for the broken rail condition is:

$$R_{NormPath\_L} = R_{NormPath\_H} + R_{BR}||R_{Extraneous} \tag{7}$$

Assuming R_{BR} is much greater than $R_{Extraneous}$, the parallel resistance term $R_{BR}||R_{Extraneous}$ can be approximated as $R_{Extraneous}$. This causes equation (5) to become:

$$I_{Gap}(R_{Extraneous}) = \frac{V}{R_{NormPath\_H}} - \frac{V}{R_{NormPath\_H} + R_{Extraneous}} \tag{8}$$

Observing the trends with respect to $R_{Extraneous}$:

$$I_{Gap}(R_{Extraneous} \to 0) = 0$$

$$I_{Gap}(R_{Extraneous} \to \infty) = \frac{V}{R_{NormPath\_H}}$$

At low extraneous resistances, the current level with a broken rail approaches the current level without a broken rail and there is very little to no gap. With higher extraneous resistances, the gap approaches the previous equation (6). A broken rail threshold should be set at a value such that a broken rail can be detected with a low extraneous resistance.

3. Capacity Analysis with NGTC

To achieve maximum capacity gains, train separation in following moves should be minimized, while abiding by train movement authorities (known as PTCEA in QMB) and other safety limits. An optimal operation that maximizes capacity is where trains operate in following moves as close as possible, but without having to decelerate to avoid a PTC penalty brake application due to the train coming within predicted braking distance of the train ahead – operating at steady-state speed.

Under Basic QMB (B-QMB) operations, trains can only enter an occupied block in following moves, limited to Restricted Speed Restriction (RSR) as the rear end of a leading train cannot be vitally determined and also because conventional track circuits cannot detect broken rail in an occupied track circuit. Capacity gains with QMB can be achieved with the integration of new technologies, namely Vital Rear-of-Train Location (VRTL), and NGTC, herein identified as Advanced QMB (A-QMB). Under A-QMB operation, a following train may be able to enter an occupied block at maximum authorized speed (MAS) up to the last reported rear end location of the leading train, as seen in Figure 10.

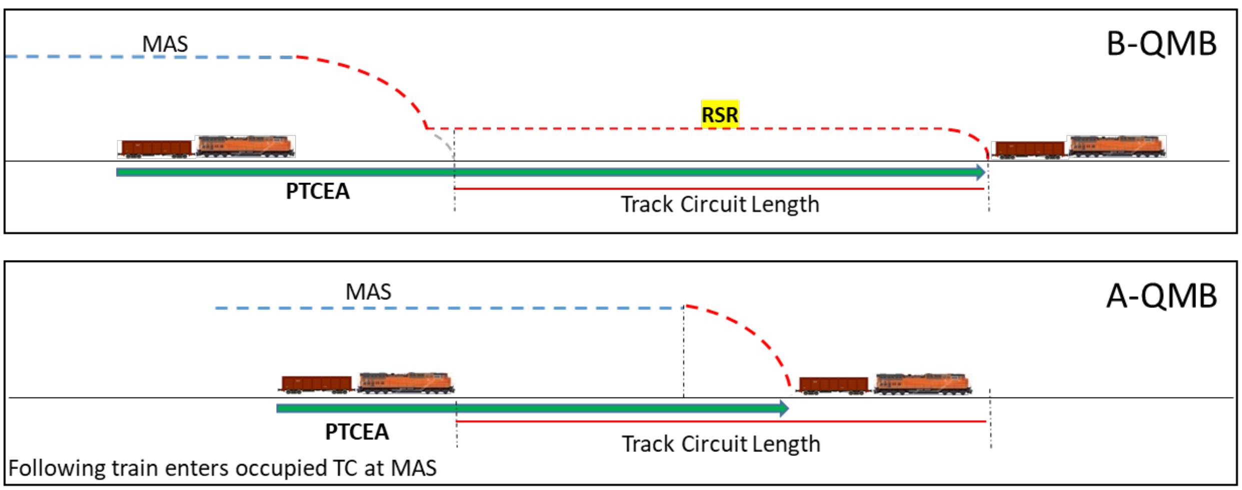


Figure 10. Theoretical representation of train separation in B-QMB and A-QMB

This study analyzed the Minimum Steady State Separation (Min SSS) between trains in following moves, which determines boundaries where following trains would start reducing speed. The study also proposes an algorithm that calculates Min SSS under different system operational scenarios. The analysis estimates potential train separation gains that can be obtained under various operational scenarios and system configurations.

The results of the analysis showed that significant reduction in train separation in following moves can be obtained with A-QMB when compared to B-QMB. The analysis also showed comparable results between A-QMB and B-QMB with halved track circuits. Appendix A contains the details of the capacity analysis.

The overall results indicated that implementing QMB with the NGTC and VRTL technologies can substantially reduce train separation and help increase railroad network efficiency, particularly in areas with dense traffic operation where following move operations are more frequent.

4. NGTC Hazard Analysis

The hazard analysis performed in this project is an early-stage analysis using the ongoing CONOPS research and high-level system design. The key purpose of this analysis is to identify new and existing hazards along with potential mitigation methods which then can be addressed in the system requirement development.

The hazards analyzed during this research are classified into six different hazard groups, as shown in Table 8. Each hazard group was analyzed in further detail, and Appendix B contains the complete analysis.

Table 8. Hazard group list

Group No.	Hazard Description
1	Spontaneous rail break
2	No distinction of single versus multiple rail breaks
3	Rollouts
4	Broken wire
5	Insulated joint malfunction
6	Undetected rail defect/partial broken rail

The analysis showed that only hazard group 3 resulted in a notable increased level of risk from current operations. The general scenario for the rollout hazard is presented as follows:

- Unattended car(s) or train doing switching in Restricted State makes unauthorized and undetected entry onto main track from siding, junction, or spur behind leading train in a close-following move.
- Leading train, rollout, and following train's PTCEA are all in same block.
- Following train can enter block at MAS.

While the rollout hazard is still improbable, the probability of collision is greater since there is less reaction time to stop – as would be the case if the following train were operating per RSR. The severity of collision may also be greater since the following train can enter occupied block at MAS. Increased risk is expected whenever increasing exposure to higher speeds.

However, the risk of the hazard remains in the I-E category, per the hazard risk matrix in Figure 11, due to the low probability of this hazard. Hazards in the I-E category can be acceptable with mitigation – through training, for example.

Severity → / ↓ Probability	I Catastrophic	II Critical	III Marginal	IV Negligible
A Frequent	UN	UN	UN	AC
B Probable	UN	UN	UN	AC
C Occasional	UN	UN	AC/WR	AC
D Remote	UN	AC/WR	AC	AC
E Improbable	AC/WR	AC	AC	AC

Integrity Goal Definitions :

UN - Unacceptable

AC/WR - Acceptable with review by the railroad's chief safety officer or designated representative

AC - Acceptable without review

Figure 11. Hazard risk index

5. Development of NGTC Requirements Specification

Appendix C contains a high-level requirement specification developed for the NGTC wayside segment. The specification includes external interface, functional, performance, safety, extensibility, and RAM requirements. Since the NGTC concept also involves the onboard segment, additional requirements were developed to be incorporated with the QMB segment-level requirements.

The NGTC wayside functional requirements can be broken down into representing the following simplified process:

1. Measure Tx and Rx signals.
2. Determine a binary value for each Tx and Rx based on TBD thresholds.
3. Use both the Tx and Rx binary values to determine the NGTC system state.
4. Use a wayside interface unit (WIU) radio to broadcast the NGTC-based WSM.

Table 9 provides the NGTC system states and WIU indications, which captures steps 3 and 4. The system state that provides the benefit of allowing MAS into an occupied block is where Tx = 1 and Rx = 0.

Table 9. NGTC System States

Tx Current	Rx Signal	Meaning	NGTC WIU Indication
0	0	Broken rail, either in unoccupied block or between Tx and shunting axle	Restricted
0	1	Not physically possible and this would indicate an NGTC failure.	NGTC is inoperable (Restricted).
1	0	• Occupancy somewhere in block • No broken rail between Tx and shunting axle • Can enter at MAS	Clear to proceed at MAS, acknowledging rollout uncertainties *
1	1	Clear	Clear to proceed at MAS

*In the case that a PTCEA extends through the entire block, this would indicate a rollout or another anomaly.

In addition to the NGTC requirements, select functionality was identified that could be developed in other segments or included as NGTC potential future enhancements. The following are recommendations for further development:

- The following safety feature is recommended for implementation in the QMB system for use when a train is operating wherever the NGTC wayside segment is implemented. Information should be included in the track database about whether there is a derail or rollout detector (e.g., O/S, also known as on sheet, on station, or occupancy sensor) installed or not at each hand-thrown switch (e.g., at sidings, junctions, and spurs) in NGTC territory. The onboard will check the track database before getting within braking distance of each hand-thrown switch in a block with an occupancy ahead, and if there is not a derail or detector installed, then the onboard will display and enforce a RSR at that switch rather than allowing operation at MAS. Additionally, if the train enters the block before the occupancy ahead clears the block, the train's onboard will enforce an RSR at each hand-thrown switch that lacks a derail or detector throughout that block.

- A broken rail location is estimated by correlating the end-of-train (EOT) (or head-of-train [HOT]) position at the time when Tx current = 0. This could be used for maintenance purposes to find the location of the broken rail within a typical track circuit length of 2 miles. Complexity is added because the office will need to collect and process information from both the onboard and wayside segments.
- Potential enhancements to the NGTC design include adding a third signal level, using analog signal levels, and using peer-to-peer communication between NGTC devices.

6. Conclusion

Researchers demonstrated the validity of an NGTC concept for broken rail and rollout detection that supports the QMB method of train control. They performed proof-of-concept testing, capacity analysis, hazard analysis, and requirements development. Researchers demonstrated there was enough of a difference in the measured current when there is a rail break and when there was not, which proved the NGTC concept. The smallest gap was created by the highest possible current level when a broken rail was present (i.e., broken rail at farthest end of track circuit) and the lowest possible current level when a broken rail was not present (i.e., unoccupied track circuit). Additionally, an electrical model of the NGTC concept was developed and validated with test data.

Static and dynamic tests were performed, followed by analyzing the results, including the development of an analytical model to accompany the field test analysis. One test of interest was the dynamic test where a single, four-axle locomotive moved away from the transmission side of the block and a broken rail was simulated after the train passed. This helped to create extreme conditions – lower shunting with the four-axle locomotive – and a broken rail 24,000 feet away from the transmission side of the block. The result demonstrated there was a respectable gap between the signals with and without a broken rail. Therefore, the basic concept of the NGTC was proven feasible.

Capacity analysis performed on the project further showed that QMB, with the NGTC concept plus VRTL, did improve capacity in terms of the minimum steady-state separation (Min SSS). Train separation reduction varied from 20.36 percent to 45.89 percent among different train types. The analysis also showed comparable train separation results between QMB with NGTC and basic QMB with half length-track circuits.

An initial qualitative hazard analysis was performed on the project identified hazards and potential mitigations, which were then reflected in the NGTC design and requirements. The analysis showed that only the rollout hazard group resulted in a notable increased level of risk from current operations. This risk remained in the I-E category, per the hazard risk matrix. Since hazards in the I-E category can be acceptable with mitigation, e.g., training users, the initial hazard analysis indicated that there were no unacceptable hazards associated with the concept.

7. References

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Kindt, J., Brosseau, J., & Polivka, A. (2018). Next Generation Track Circuits [DOT/FRA/ORD-18/10]. Washington, DC: Federal Railroad Administration.

AREMA. (2012). Recommended Formulae for Computing Minimum Allowable Resistance Between Track Battery and Track and for Computing Related Current. (2012). In *AREMA C&S Manual.*

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
A	Amp (measure of electrical current)
AG	Advisory Group
A-QMB	Advanced Quasi-Moving Block – refers to an advanced QMB system that is equipped with NGTC and VRTL
AREMA	American Railway Engineering Maintenance of Way Association
B-QMB	Basic Quasi-Moving Block
CBTC	Communication Based Train Control
CONOPS	Concept of Operation
CTC	Centralized Track Control
EO-PTC	Enhanced Overlay PTC
EOT	End of Train
FMB	Full Moving Block
FRA	Federal Railroad Association
HOT	Head-of-Train
IJ	Insulated Joint
ITC	Interoperable Train Control
MAS	Maximum Authorized Speed
MinSSS	Minimum Steady State Separation
NGTC	Next Generation Track Circuit
O-PTC	Overlay PTC – refers to the ITC PTC system, or a subset thereof, without the incorporation of QMB functionality
PTC	Positive Train Control
PTCEA	PTC Exclusive Authorities
QMB	Quasi Moving Block
RSIA'08	Railroad Safety Improvement Act of 2008
RSR	Restricted Speed Restriction
Rx	Receiving end – refers to the track circuit receiving end
SMU	Source-Measuring Unit
TC	Track Circuits
TTC	Transportation Technology Center
TTT	Transit Test Track
Tx	Transmission end – refers to the track circuit transmission end
VRTL	Vital Rear-of-Train Location
WIU	Wayside Interface Unit
WSM	Wayside Status Message

Appendix A. Capacity Analysis

A1. Background and Scope

This document provides an analysis of train operation performance when Next Generation Track Circuit (NGTC) and Vital Rear-of-Train Location (VRTL) technologies are implemented in conjunction with the Quasi-Moving Block (QMB) train control method, identified as Advanced QMB (A-QMB). The analysis was developed considering minimum achievable separation for a pair of trains in following moves in ideal theoretical operational scenarios. Performance of trains under A-QMB was compared with the basic QMB implementation (B-QMB) where these technologies are not used and with a B-QMB configuration where conventional track circuits (TC) are split in half. The analysis considered different train types, track speeds, and operation conditions. An algorithm is proposed that attempts to minimize train separation for various scenarios.

A1.1 Background

Capacity of the track is based on the number of trains allowed to operate in the same track at the same time while maintaining track speed. That depends mainly on the separation distance required between trains (i.e., train separation between the end of a leading train and the head of a following train) to maintain safe operation and the maximum authorized speed (MAS) of trains operating on the track. This analysis estimates the theoretical minimum separation between trains in following moves, which can maximize capacity and train speeds using A-QMB while maintaining safe operation.

Under B-QMB operations, trains can only enter an occupied block in following moves, limited to Restricted Speed Restriction (RSR), while in A-QMB a following train may be able to enter an occupied block at MAS up to the last reported rear end location of the leading train prior to the following train entering the block. This study analyzes the minimum separation between trains in following moves that could avoid a following train to trespass the boundaries where speed restrictions are imposed that would cause inefficient operation and subsequent loss of capacity. Out of the analysis, an algorithm is introduced to calculate the required minimum separation for trains in following moves.

A1.2 Scope

This document investigates train operation performance in train following moves when NGTC and VRTL technologies are implemented in conjunction with QMB. The analysis also investigated potential gains with full-moving block (FMB).

Theoretical analyses were conducted to estimate capacity gains under various operational scenarios and system configuration. The analysis was developed considering minimum achievable separation for a pair of trains in following moves, which provides an estimation of potential capacity increase. The analysis did not include an estimation of railroad network capacity gains.

The analysis included latency introduced by multiple system components during the operation of following train moves. The results obtained in this report are subject to the typical latency values assumed for the calculations.

Researchers developed an analytical model that calculates minimum separation between a pair of trains for an ideal following move scenario (i.e., not a network analysis) to produce results that give an insight for potential capacity gains.

A1.3 Organization of the Capacity Analysis Report

This document is organized as follows:

- Background and Scope
- Reference Documents
- Capacity Analysis Overview
- Minimum Separation for Optimal Operation (Methodology, Results, and Enhancements)
- Conclusion
- Appendix A-1 – Main Concepts in QMB
- Appendix A-2 – Time Delays that Affect Margins in B-QMB and A-QMB

A2. Reference Documents

Table A1 lists the documents referenced in this capacity analysis report. The NGTC Concept of Operations (ConOps) document is a companion to this capacity analysis. The project team recommend the ConOps be read before or in conjunction with this report. The capacity analysis highlights NGTC capacity benefits when implemented with QMB train control methods. Therefore, the reader should have sufficient background about the QMB train control method which can be obtained by referring to the QMB Concept of Operations document and more details about requirements of the system in QMB System Requirements and QMB Onboard Segment Requirements documents.

Table A1. Referenced documents

NGTC Concept of Operations
QMB Concept of Operation
QMB System Requirements
QMB Onboard Segment Requirements
NGTC Requirements Specification

A3. Minimum Train Separation for Optimal Operation

This section discusses the minimum train separation for optimizing operations.

A3.1 Minimum Steady-State Separation (Min SSS) Concepts

To achieve maximum capacity gains, train separation in following moves should be minimized, while abiding by train movement authorities (known as PTC Exclusive Authorities, or PTCEA, in QMB) and other margin limits. An optimal operation that maximizes capacity is where trains operate in following moves as close as possible, but without having to decelerate to avoid a PTC penalty brake application. In a scenario where a train reaches its braking curve in a following move, it would have to decelerate, as shown as a sequence of time (from t1 to t4), in Figure A1. Note that the numbered circles 1, 2, 3, and 4 in Figure A1 indicate the states of the train operating at MAS, deceleration, restricted speed restriction (RSR) and acceleration, respectively. The orange circles indicate the current state of the train in each time step.

As the leading train moves in times t2 and t3, the zero-mph target at the end of the PTCEA of the following train (within the occupied block) will change to an RSR target once it receives a PTCEA extension. The RSR will be removed from the occupied block once the leading train clears the TC of that block. The process of decelerating, operating at RSR and accelerating back to MAS imposes major losses on train performance, as well as energy efficiency, which can be extremely significant in areas with high train density. Additionally, keeping unnecessary large headways prevents the realization of potential track capacity gains.

BQM in Figure A1 is the Basic QMB Margin, which is the last known location of the rear-end of a leading train by a following train. BQM includes multiple factors such as rear-of-train location uncertainty, message communication delay and others, which are depicted later in this analysis.

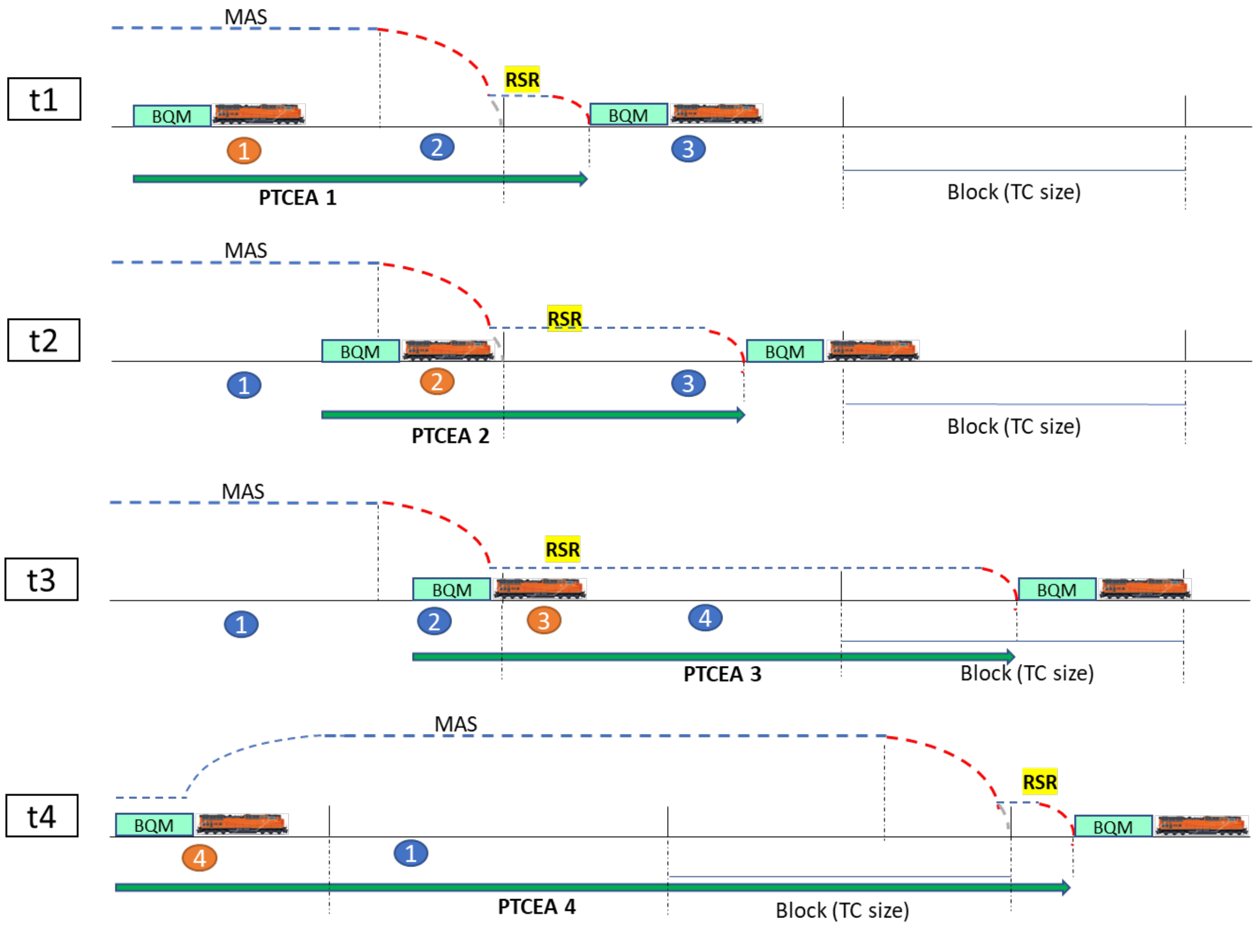

Figure A1. Train separation increases when a following train enters the braking curve in B-QMB operation

This undesired train deceleration/acceleration sequence can be avoided by maintaining a minimum separation distance between trains in Close Following Move (CFM) operation, where a following train can determine the limit where it would have to start reducing speed based on the next block length and the rear-end position of a leading train. In CFM operation, a leading train periodically rolls up its PTCEA based on a predetermined rate (CFM rollup rate).

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 estimate when the leading train would leave that block and adjusts its own speed. In such case, both trains will be operating at approximately the same speed with almost constant pacing where changes in the speed of the leading train will directly impact the speed of the following train, establishing a Min SSS condition. When Min SSS is established, the following train will be able to lift the RSR and extend its braking curve to the beginning of the next block, without having to start deceleration, as illustrated in time steps t2 and t3 in Figure A2.

A3.1.1 Minimum SSS for B-QMB

The Min SSS for B-QMB (Min $SSS_{B\text{-}QMB}$) operation is given in (1).

$$\text{Min SSS}_{\text{B-QMB}} = TC_L + BC_0 + M_{TC} \quad (1)$$

where

$$M_{TC} = [(T_{TCr} + T_{WSM}) * S_{L\text{-}trn}/3600] \quad (2)$$

The factors included in equation (1) are:

- TC_L - Length of the TC
- BC_0 - Braking distance of the following train up to a Full Stop
- M_{TC} - Time required to convey to the following train that the TC in a block is Clear, converted to distance (based on leading train's speed)

The margin components for M_{TC}, given in (2), include the following:

- T_{TCr} - TC release time, i.e., time that it takes for the circuitry to change the TC indication.
- T_{WSM} - Wayside Status Message (WSM) periodic broadcast frequency.
- $S_{L\text{-}trn}$ - Speed of the leading train.

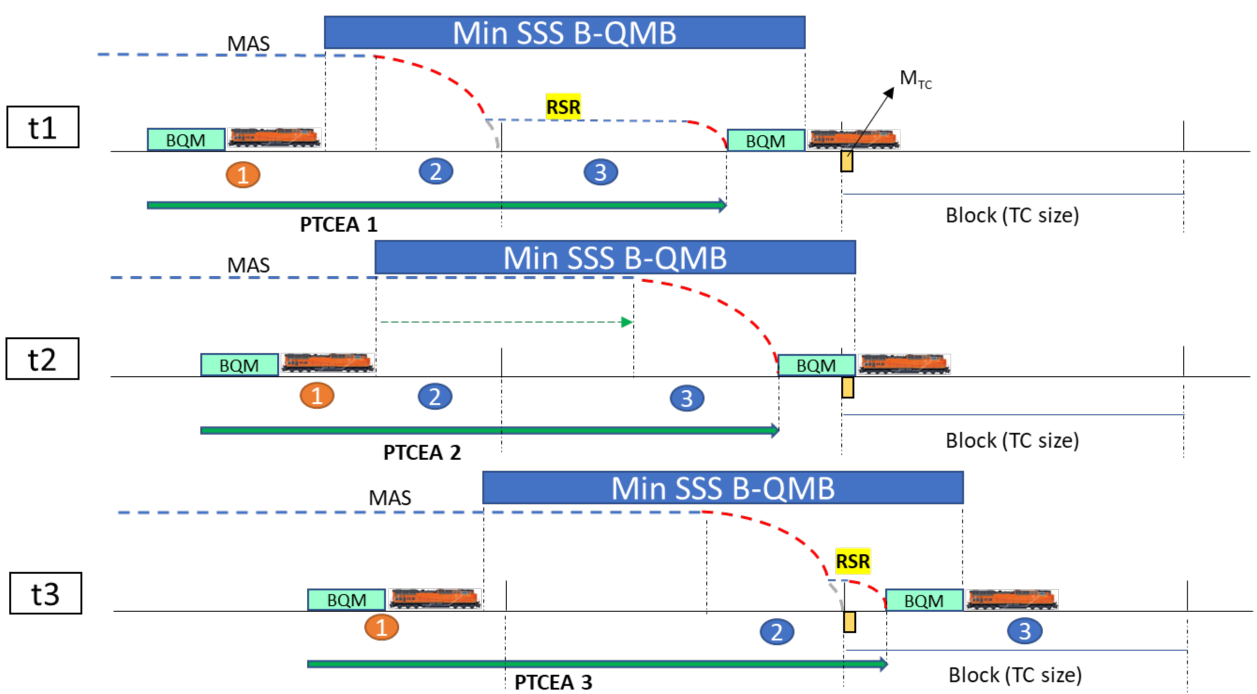

Figure A2. Minimum train separation in B-QMB operation

Note that for the purpose of this analysis, BQM is assumed to be shorter than the length of the TC, and therefore, BQM does not influence the Min $\text{SSS}_{\text{B-QMB}}$ calculation.

A 3.1.2 Minimum SSS for A-QMB

Achieving maximum capacity gain in A-QMB will require a following train to maintain a Min SSS from a leading train in a following move operation. If the following train enters its braking curve limit, it will have to decelerate 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 passed the beginning of its braking curve deceleration, as illustrated in Figure A3. Note that if the following train passes the last reported location of the leading train at the time the following train enters the occupied block, before the leading train clears the block, the following train will need to maintain RSR until the end of that block even if the leading train has cleared it already. That is because the leading train could have caused a broken rail immediately after that last reported location and NGTC would not be able to detect it.

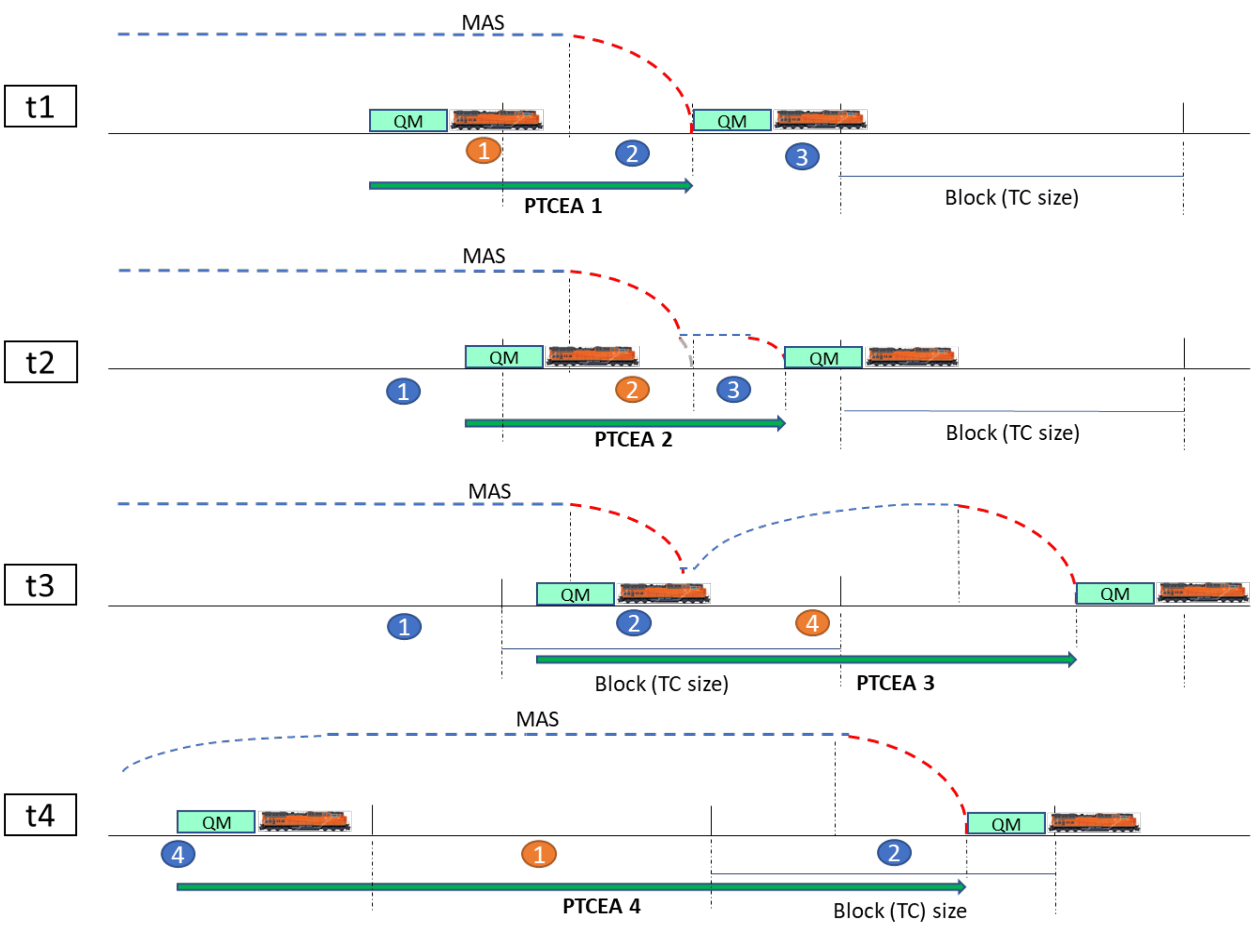

Figure A3. Excess train headway separation when a Min SSS is not maintained during A-QMB operation

Although the headway separation in Figure A3 is shorter than that of the B-QMB case, since a following train is allowed to enter an occupied block at MAS under A-QMB operation, this would still likely affect potential higher track capacity gains in territories with high density train operation.

Figure A4 and Figure A5 illustrate Min SSS for A-QMB (Min $SSS_{A\text{-}QMB}$) operation, where a following train extends its PTCEA before entering its braking curve limit. Figure A4 illustrates the scenario where the Min SSS is determined based on the TC length, the braking curve distance and QM, referred to as Min SSS $M_{TC\ A\text{-}QMB}$. Figure A5 shows the case where the Min SSS is based on the following train's braking curve distance and QM, referred to as Min SSS $QM_{A\text{-}QMB}$.

Figure A5 shows the effective real time separation that QM imposes in scenarios where the Min SSS is dictated by the braking curve and QM. The distance caused by the delays in QM is variable where t1 illustrates QM the moment immediately before the CFM rollup rate (typically 16 seconds) is triggered, while t2 illustrates QM the moment the following train receives a PTCEA extension based on the leading train's PTCEA rollup. Because the timer since the last rollup counts from 0 to 16 seconds, QM increases until the next CFM rollup is triggered again, which will result in the rollup of the leading train's PTCEA and the reduction of QM.

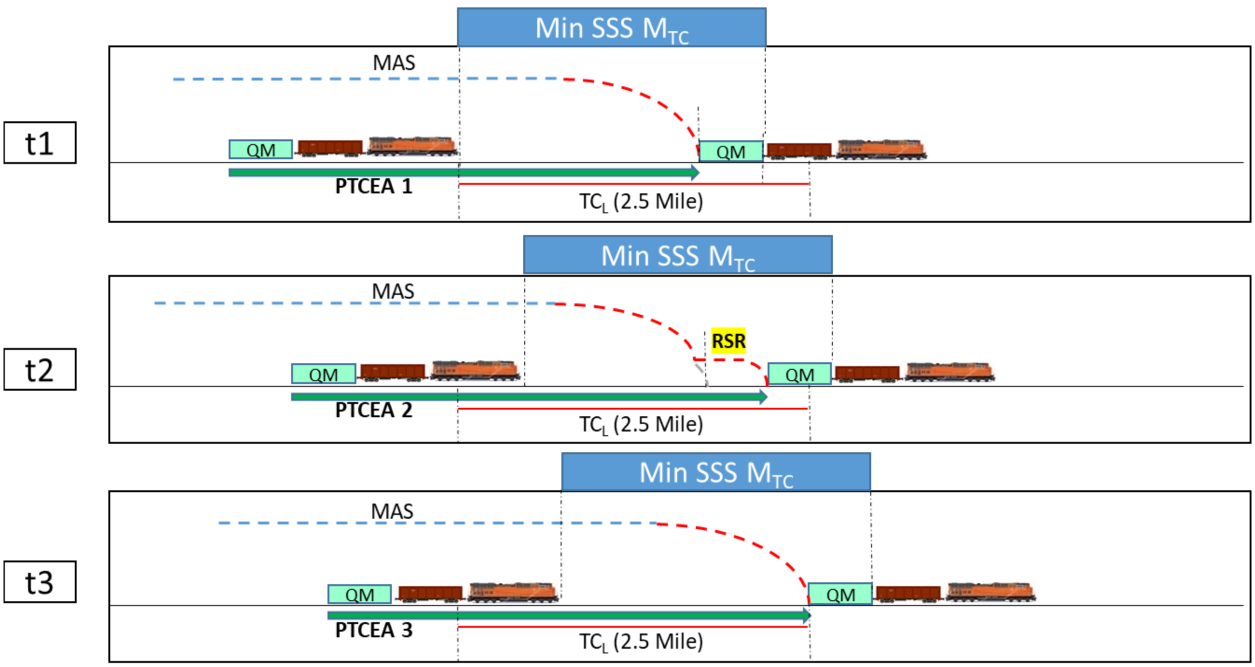

Figure A4. Min SSS based on TC length, braking curve to RSR and QM

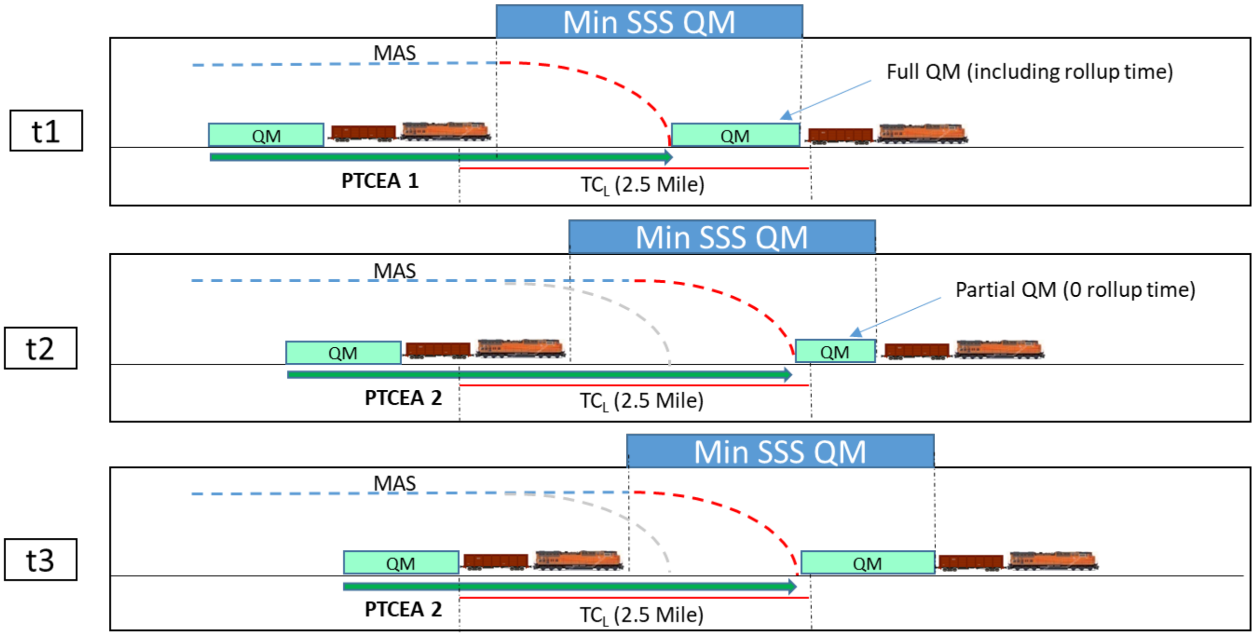

Figure A5. Min SSS based on the braking curve and QM

Min $SSS_{A\text{-}QMB}$ is the minimum steady state separation between trains in A-QMB operation, BC_0 is the braking distance of the following train up to a full stop, and $QM_{A\text{-}QMB}$ is the margin under A-QMB operation, which includes all the delays incurred until the following train updates its PTCEA. Min $SSS_{A\text{-}QMB}$ is calculated using the equations in (3), (4), and (5). To avoid entering the braking curve zone, the larger value of the two equations in (3) and (4) is the Min SSS.

The margins for A-QMB are given in (5) as follows:

- $T_{roll\text{-}up}$: roll-up rate in close following moves (nominally 16 seconds).
- T_{PTCmsg}: PTC Superframe duration for each PTC message.
- D_{SM}: safety margin, which includes VRTL inaccuracy error and allowance for train stretching.
- $T_{re\text{-}trans}$: average retransmission time of PTC messages.
- T_{PhL}: physical layer delays which include the communication backbone delay and processing delays of the onboard computers, back office server, PTCEA parser, and radios.

$$\text{Min SSS } M_{TC\ A\text{-}QMB} = (TC_L + BC_0)/2 + QM_{A\text{-}QMB} \tag{3}$$

$$\text{Min SSS } QM_{A\text{-}QMB} = (BC_0 + QM_{A\text{-}QMB}) \tag{4}$$

$$QM_{A\text{-}QMB} = [(T_{roll\text{-}up} + T_{PTCmsg} + T_{re\text{-}trans} + T_{PhL}) * S_{L\text{-}trn}/3600] + D_{SM} \tag{5}$$

If, $$BC_0 \geq ½\ TC \tag{6}$$

Then, Min SSS = Min $SSS\ QM_{A\text{-}QMB}$

Assumptions made for the calculation of Min SSS include:

- 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 such that a following train can match it.
- The trains are in CFM mode, which implies having a fixed rollup rate by the leading train.
- The TC 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 PTCEA "To" limit of the following train extends beyond the boundary at the end of the occupied block, see QMB onboard requirements for NGTC functionality.

In some cases, such as when the following train is heavy, the braking curve could be sufficiently large that the leading train could release the block before the following train reaches its braking curve limit. However, in short track circuits, this could cause the following train to reach its braking curve limit before the leading train clears the block. In such scenarios, the braking curve distance plus the A-QMB Margin (QM) would dictate the Min SSS upon satisfying the condition in equation (6), as illustrated in Figure A6.

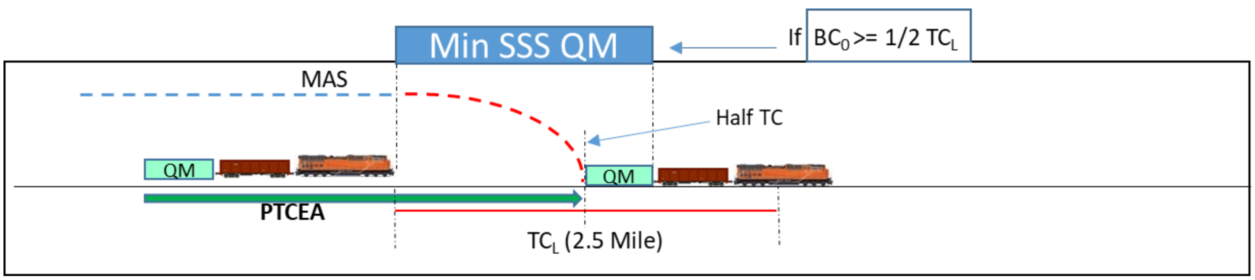

Figure A6. Illustration of the condition that allows using lower Min SSS distance equal to Min SSS QM

Figure A7 presents a proposed algorithm for Min SSS calculation. The first step is to match the speed of the leading train using a pacing algorithm. After that, the Min SSS equations in (3) and (4) are calculated including the margin in (5) as well as the inequality condition in (6). Next, the Min SSS is determined based on the algorithm results according to the condition and equations values. If the condition is satisfied or if the Min SSS QM is larger than Min SSS M_{TC}, then Min SSS is equal to Min SSS QM. Otherwise, Min SSS is equal to Min SSS M_{TC}.

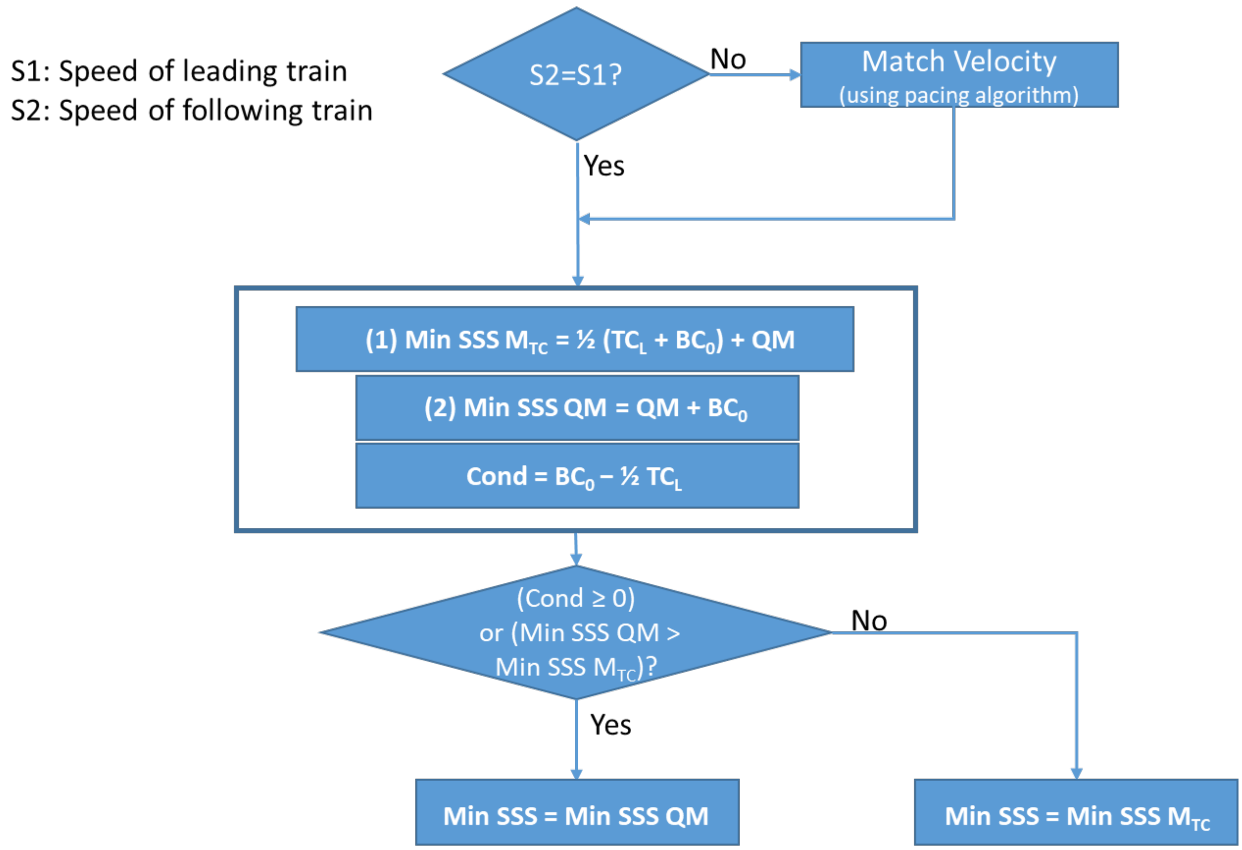

Figure A7. Flow chart for an algorithm to calculate the Min SSS in A-QMB

A3.2 Modeling Approach and Operational Scenarios

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

- Single track operation, pre-determined TC lengths
- Tracks without curvature on flat grade
- Three types of trains (Loaded Freight, Expedited, and Passenger) with typical average deceleration rates
- Train separation calculated for pair of trains with the same train type
- RSR of 20 mph
- Analysis of operational scenarios for the following configuration – one per turn:
    - Three TC lengths: 1.24, 2.45, and 4.5 miles
    - Loaded 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 A2 shows the deceleration rates used for the three types of trains. These values are average numbers obtained from the analysis developed under other Federal Railroad Administration

(FRA) projects (the HRCTC* and RAM Phase 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 A2. Train deceleration rates

	Freight	Passenger	Expedited
Deceleration Rate (mph/h)	1,000	4,000	3,500

A3.3 Min SSS Comparison Results

Table A3 shows an example of Min SSS calculation without margins in B-QMB and A-QMB for a given scenario. The results show that Min SSS in B-QMB is two times that of A-QMB, when margins are not included as a first simplified theoretical calculation.

Table A3. Example of Min SSS calculation for B-QMB and A-QMB without margins

	Value	Unit
Deceleration braking rate	1000	mph/h
Acceleration rate RSR to MAS	500	mph/h
MAS	60	mph
RSR	20	mph
Block Length	2.5	Miles
Braking distance to full stop (60 to 0)	1.80	Miles
B-QMB Min SSS*	**4.30**	Miles
A-QMB Min SSS**	**2.15**	Miles

*Obtained using equation (1) without considering margins

** Obtained using equation (3) without considering margins

Table A4 and Table A5 contain detailed train separation assessments that consider the different margins of B-QMB and A-QMB operation. Table A4 presents a set of various scenarios of different train types, speeds, and TC lengths, along with the braking curve distance to full stop as well as the calculation of margins. Table A5 shows the results for the A-QMB Min SSS candidate equations for each scenario, a condition status in equation (6) that compares the braking curve distance to the TC length, the Min SSS outcome for both B-QMB and A-QMB, and the proportional Min SSS gain for A-QMB compared to B-QMB.

Min SSS results in Table A5 are highlighted in different colors according to the equation that dictates the Min SSS calculation. Cells highlighted in blue indicate that Min SSS M_{TC} is used when it is greater than Min SSS QM, while not satisfying the exception condition. The yellow

* FRA project "Higher Reliability and Capacity Train Control."

† FRA project "PTC Reliability, Availability, and Maintainability (RAM) Study Phase II."

cells indicate that Min SSS QM is used, when its value is greater than Min SSS M_{TC}. The green cells indicate that Min SSS QM is used, although Min SSS M_{TC} is greater than Min SSS QM, due to satisfying the condition in equation (6). The Min SSS gain column shows the proportional reduction of Min SSS in A-QMB compared to B-QMB with normal TC size (not halved).

Table A4. QM calculation for multiple operational scenarios

Train Type	MAS (mph)	BC_0 (miles)	TC_L (miles)	M_{TC} (miles)	QM (miles)
Freight	60	1.80	1.2	0.13	0.60
Expedited	60	0.51	1.2	0.13	0.60
Passenger	79	0.78	1.2	0.18	0.79
Freight	60	1.80	2.5	0.13	0.60
Expedited	60	0.51	2.5	0.13	0.60
Passenger	79	0.78	2.5	0.18	0.79
Freight	60	1.80	4.5	0.13	0.60
Expedited	60	0.51	4.5	0.13	0.60
Passenger	79	0.78	4.5	0.18	0.79
Freight	49	1.20	1.2	0.11	0.49
Expedited	49	0.34	1.2	0.11	0.49
Passenger	59	0.44	1.2	0.13	0.59
Freight	49	1.20	2.5	0.11	0.49
Expedited	49	0.34	2.5	0.11	0.49
Passenger	59	0.44	2.5	0.13	0.59
Freight	49	1.20	4.5	0.11	0.49
Expedited	49	0.34	4.5	0.11	0.49
Passenger	59	0.44	4.5	0.13	0.59

Table A5. Min SSS gain for various B-QMB and A-QMB scenarios

Train Type	MAS (mph)	TC_L (miles)	B-QMB Min SSS (miles)	A-QMB Min SSS M_{TC} (1) (miles)	A-QMB Min SSS QM (2) (miles)	Diff 2-1 (miles)	Cond > 0?	A-QMB Min SSS (miles)	Min SSS gain A-QMB vs B-QMB
Freight	60	1.2	3.13	2.10	2.40	0.30	1.20	2.40	23.43%
Expedited	60	1.2	1.85	1.46	1.11	-0.34	-0.09	1.46	21.18%
Passenger	79	1.2	2.16	1.78	1.57	-0.21	0.18	1.57	27.22%
Freight	60	2.5	4.43	2.75	2.40	-0.35	0.55	2.40	45.89%
Expedited	60	2.5	3.15	2.11	1.11	-0.99	-0.74	2.11	33.09%
Passenger	79	2.5	3.46	2.43	1.57	-0.86	-0.47	2.43	29.71%
Freight	60	4.5	6.43	3.75	2.40	-1.35	-0.45	3.75	41.72%
Expedited	60	4.5	5.15	3.11	1.11	-1.99	-1.74	3.11	39.66%
Passenger	79	4.5	5.46	3.43	1.57	-1.86	-1.47	3.43	37.15%
Freight	49	1.2	2.51	1.69	1.69	0.00	0.60	1.69	32.66%
Expedited	49	1.2	1.65	1.26	0.83	-0.43	-0.26	1.26	23.68%
Passenger	59	1.2	1.77	1.41	1.02	-0.38	-0.16	1.41	20.36%
Freight	49	2.5	3.81	2.34	1.69	-0.65	-0.05	2.34	38.59%
Expedited	49	2.5	2.95	1.91	0.83	-1.08	-0.91	1.91	35.27%
Passenger	59	2.5	3.07	2.06	1.02	-1.03	-0.81	2.06	32.93%
Freight	49	4.5	5.81	3.34	1.69	-1.65	-1.05	3.34	42.52%
Expedited	49	4.5	4.95	2.91	0.83	-2.08	-1.91	2.91	41.22%
Passenger	59	4.5	5.07	3.06	1.02	-2.03	-1.81	3.06	39.67%

Figure A8 and Figure A9 show the Min SSS for freight trains with different TC sizes at MAS of 60 and 49 mph, respectively. In both figures, the A-QMB Min SSS curve takes the highest value between the A-QMB Min SSS M_{TC} and A-QMB Min SSS QM curves, except when the condition (in equation 6) is satisfied, and in that exceptional case, the Min SSS is assigned to the Min SSS QM value. This can be seen in the 2.5 miles TC length case at 60 mph MAS, as shown in Figure A8.

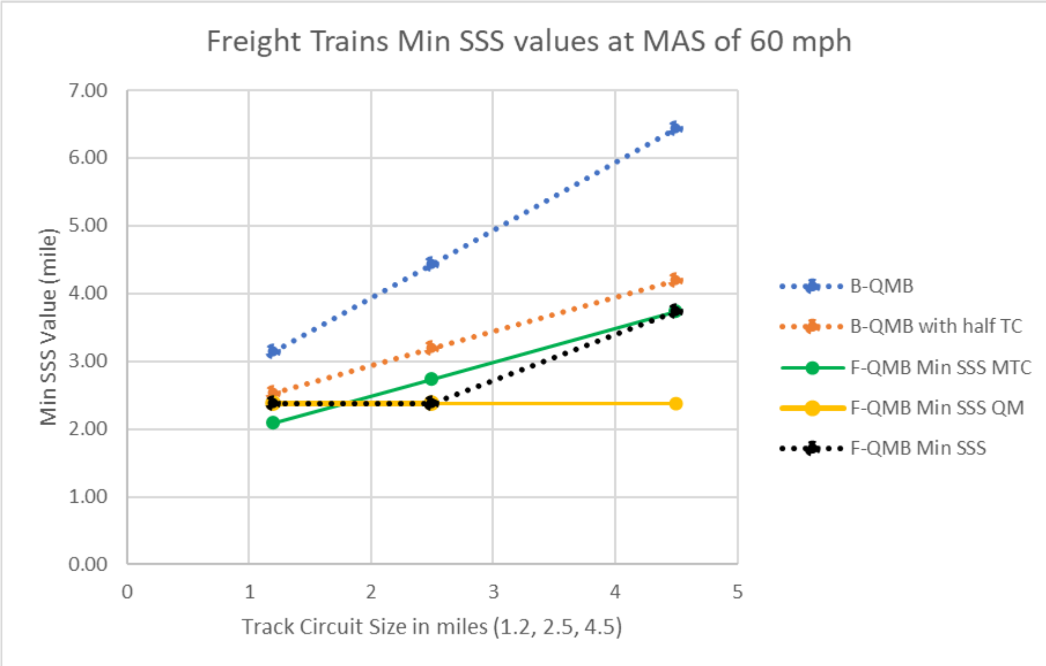

Figure A8. Min SSS for freight trains at MAS of 60 mph

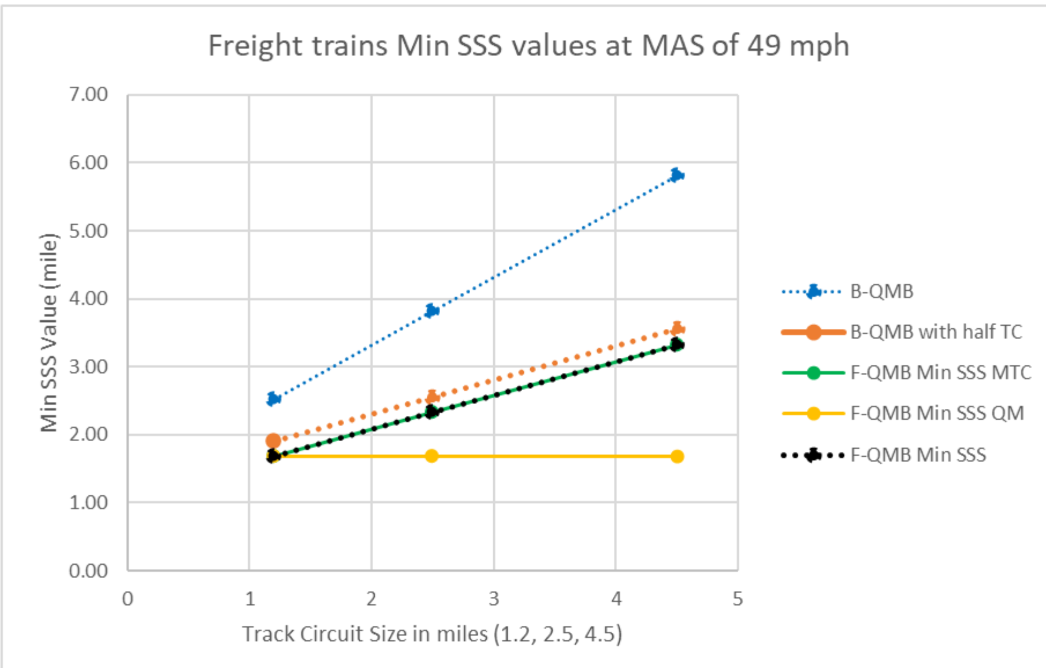

Figure A9. Min SSS for freight trains at MAS of 49 mph

Table A6 shows a comparison between A-QMB and B-QMB with half TCs as well as FMB and A-QMB. The cells highlighted in gray indicate the cases where A-QMB has shorter Min SSS than B-QMB with half TCs. Negative percentages indicate that Min SSS in A-QMB is longer than that of B-QMB with half TCs.

A-QMB showed better performance than B-QMB with half TC lengths in all freight train scenarios. For passenger and expedited trains, B-QMB with half TCs perform better than A-QMB.

The overall conclusion is that heavier trains (i.e., freight trains) with longer braking curves have better train separation results in A-QMB when compared to B-QMB with half TCs. Lighter trains (i.e., passenger and expedited trains) have the opposite effect, because in B-QMB, the train's braking curve has a high influence in the calculation of Min SSS relative to the TC length, compared to A-QMB.

Table A6. Comparison of Min SSS gain between Basic QMB with half TC length and A-QMB, and also FMB and A-QMB

Train Type	MAS (mph)	TC_L (miles)	B-QMB Min SSS (with half TC_L) (miles)	A-QMB Min SSS (miles)	A-QMB versus B-QMB with half TC_L gain	Min SSS gain of FMB versus A-QMB
Freight	60	1.2	2.53	2.40	5.3%	0%
Expedited	60	1.2	1.25	1.46	-16.7%	24%
Passenger	79	1.2	1.56	1.57	-0.9%	0%
Freight	60	2.5	3.18	2.40	24.6%	0%
Expedited	60	2.5	1.90	2.11	-11.0%	47%
Passenger	79	2.5	2.21	2.43	-10.1%	35%
Freight	60	4.5	4.18	3.75	10.4%	36%
Expedited	60	4.5	2.90	3.11	-7.2%	64%
Passenger	79	4.5	3.21	3.43	-7.0%	54%
Freight	49	1.2	1.91	1.69	11.5%	0%
Expedited	49	1.2	1.05	1.26	-19.9%	34%
Passenger	59	1.2	1.17	1.41	-20.6%	27%
Freight	49	2.5	2.56	2.34	8.6%	28%
Expedited	49	2.5	1.70	1.91	-12.3%	56%
Passenger	59	2.5	1.82	2.06	-13.2%	50%
Freight	49	4.5	3.56	3.34	6.2%	49%
Expedited	49	4.5	2.70	2.91	-7.7%	71%
Passenger	59	4.5	2.82	3.06	-8.5%	66%

Some assumptions, based on estimates, have been made for the margins, which include the following (see Appendix A-2 for further details):

- Safety margin is determined based on the VRTL inaccuracy error plus an allowance for train stretching. 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:
  - 6 seconds timeout for unreceived acknowledgement and waiting time
  - 0.75 second reprocessing time
  - 4 seconds for new PTC message
  - 0.1 second backbone communication delay
  - For 3 messages: 3*(6+0.75+4) + 2*(0.1) = 32.45 seconds
  - At a probability of 10 percent, average retransmission delay = 32.45 seconds * 0.1 = 3.2 seconds
- Physical layer delay is assumed to be 4.7 seconds. Physical layer delays include: (1) 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) processing delay of 4.5 seconds (0.75 second at each stage, i.e., VRTL, onboard of a leading train, QMB server rollup processing, PTCEA parser, QMB server processing of new PTCEA, onboard of a following train); see Appendix B for more details.
- Roll-up rate of 16 seconds. This can be increased or decreased based on the setting of the CFM mode or time-based rollups.

Therefore, a total of 35.945 seconds is added to the margin of the Min SSS distance in A-QMB. For B-QMB, assuming only TC releases are needed to be received by the following train, an estimate of 8 seconds, converted to distance in miles, is added to the Min SSS distance in what is referred to as M_{TC}.

A3.4 System Enhancements to Reduce Min SSS in A-QMB

The lifting of the RSR imposed on a following train in a double-occupied TC depends on the following train receiving an extension of its PTCEA to at least the boundary of the TC. The PTCEA extension of a following train depends on the PTCEA rollup of a leading train, which occurs periodically, based on the CFM rollup rate. One way to increase capacity with A-QMB is to detect the leading train's clearance of the double-occupied block faster than the periodic time-based rollup method. Two ways are suggested to detect train clearance faster:

- Instant rollup upon TC clearance in CFM

In this setting, a leading train would operate with time-based CFM rollup rate, while applying instant PTCEA rollups once its EOT indicates the train has cleared a TC. The corresponding Min SSS equations for this setting are given in (7), (8), and (9).

$$\text{Min SSS } M_{TC\ A\text{-}QMB}\ E1 = (TC_L + BC_0)/2 + QM_{A\text{-}QMB} - ½\ M_{Roll\text{-}up} \quad (7)$$

Where,

$$M_{Roll\text{-}up} = T_{roll\text{-}up} * S_{L\text{-}trn}/3600 \quad (8)$$

If,

$$BC_0 \geq ½\ (TC - M_{Roll\text{-}up}) \quad (9)$$

Then,

$$\text{Min SSS} = \text{Min SSS } QM_{A\text{-}QMB}$$

Note that Min SSS $M_{TC\ A\text{-}QMB}$ E1 is the Min SSS based on clearing the TC by instant rollup and $M_{Roll\text{-}up}$ is the margin based on the CFM rollup rate. Table A7 shows the corresponding train separation gains based on Min SSS enhancement through instant leading train's PTCEA rollups when clearing TCs.

- NGTC detection of leading train's clearance of a double-occupied block

In this setting, NGTC would be able to detect a leading train's clearance from a double-occupied block and sends a WSM to the following train conveying that indication. The corresponding Min SSS equations are given in (10) and (11).

$$\text{Min SSS } M_{TC\ A\text{-}QMB}\ E2 = (QM_{A\text{-}QMB} + M_{TC} + TC_L + BC_0)/2 \quad (10)$$

If,

$$BC_0 + ½\ QM \geq ½\ (TC + M_{TC}) \quad (11)$$

Then,

$$\text{Min SSS} = \text{Min SSS } QM_{A\text{-}QMB}$$

Min SSS MTC A-QMB E2 is the Min SSS based on NGTC detection of a leading train's clearance of a double-occupied block. Table A8 shows the corresponding Min SSS gains based on the Min SSS enhancement. Table A9 shows the corresponding Min SSS gain comparison between A-QMB with default Min SSS equations and A-QMB enhancements.

Table A7. Min SSS results of various operational scenarios with instant rollup at TC boundary

Train Type	MAS (mph)	TC_L (miles)	B-QMB Min SSS (mile)	A-QMB Min SSS M_{TC} E1 (1) (miles)	A-QMB Min SSS QM (2) (miles)	Diff 2-1 (miles)	Cond > 0?	A-QMB Min SSS	Min SSS gain A-QMB versus B-QMB
Freight	60	1.2	3.13	1.97	2.40	0.43	1.33	2.40	23.43%
Expedited	60	1.2	1.85	1.32	1.11	-0.21	0.05	1.11	39.74%
Passenger	79	1.2	2.16	1.60	1.57	-0.03	0.36	1.57	27.22%
Freight	60	2.5	4.43	2.62	2.40	-0.22	0.68	2.40	45.89%
Expedited	60	2.5	3.15	1.97	1.11	-0.86	-0.60	1.97	37.32%
Passenger	79	2.5	3.46	2.25	1.57	-0.68	-0.29	2.25	34.79%
Freight	60	4.5	6.43	3.62	2.40	-1.22	-0.32	3.62	43.80%
Expedited	60	4.5	5.15	2.97	1.11	-1.86	-1.60	2.97	42.25%
Passenger	79	4.5	5.46	3.25	1.57	-1.68	-1.29	3.25	40.37%
Freight	49	1.2	2.51	1.58	1.69	0.11	0.71	1.69	32.66%
Expedited	49	1.2	1.65	1.15	0.83	-0.32	-0.15	1.15	30.27%
Passenger	59	1.2	1.77	1.28	1.02	-0.25	-0.03	1.28	27.78%
Freight	49	2.5	3.81	2.23	1.69	-0.54	0.06	1.69	55.64%
Expedited	49	2.5	2.95	1.80	0.83	-0.97	-0.80	1.80	38.96%
Passenger	59	2.5	3.07	1.93	1.02	-0.90	-0.68	1.93	37.20%
Freight	49	4.5	5.81	3.23	1.69	-1.54	-0.94	3.23	44.39%
Expedited	49	4.5	4.95	2.80	0.83	-1.97	-1.80	2.80	43.42%
Passenger	59	4.5	5.07	2.93	1.02	-1.90	-1.68	2.93	42.25%

Table A8. Min SSS results of various operational scenarios with NGTC detection of a leading train's clearance of a double-occupied block

Train Type	MAS (mph)	TC_L (miles)	B-QMB Min SSS (miles)	A-QMB Min SSS M_{TC} E2 (1) (miles)	A-QMB Min SSS QM (2) (miles)	Diff 2-1 (miles)	Cond > 0?	A-QMB Min SSS	Min SSS gain of A-QMB versus B-QMB
Freight	60	1.2	3.13	1.87	2.40	0.53	1.43	2.40	23.43%
Expedited	60	1.2	1.85	1.22	1.11	-0.11	0.15	1.11	39.74%
Passenger	79	1.2	2.16	1.47	1.57	0.10	0.49	1.57	27.22%
Freight	60	2.5	4.43	2.52	2.40	-0.12	0.78	2.40	45.89%
Expedited	60	2.5	3.15	1.87	1.11	-0.76	-0.50	1.87	40.48%
Passenger	79	2.5	3.46	2.12	1.57	-0.55	-0.16	2.12	38.59%
Freight	60	4.5	6.43	3.52	2.40	-1.12	-0.22	3.52	45.34%
Expedited	60	4.5	5.15	2.87	1.11	-1.76	-1.50	2.87	44.18%
Passenger	79	4.5	5.46	3.12	1.57	-1.55	-1.16	3.12	42.77%
Freight	49	1.2	2.51	1.50	1.69	0.19	0.79	1.69	32.66%
Expedited	49	1.2	1.65	1.07	0.83	-0.24	-0.07	1.07	35.19%
Passenger	59	1.2	1.77	1.18	1.02	-0.15	0.06	1.02	42.01%
Freight	49	2.5	3.81	2.15	1.69	-0.46	0.14	1.69	55.64%
Expedited	49	2.5	2.95	1.72	0.83	-0.89	-0.72	1.72	41.71%
Passenger	59	2.5	3.07	1.83	1.02	-0.80	-0.59	1.83	40.39%
Freight	49	4.5	5.81	3.15	1.69	-1.46	-0.86	3.15	45.79%
Expedited	49	4.5	4.95	2.72	0.83	-1.89	-1.72	2.72	45.06%
Passenger	59	4.5	5.07	2.83	1.02	-1.80	-1.59	2.83	44.19%

Table A9. Min SSS gains comparison between A-QMB with default Min SSS equations and A-QMB enhancements

Train Type	MAS (mph)	TC_L (miles)	Min SSS gain default	Min SSS gain E1	Min SSS gain E2
Freight	60	1.2	23.43%	23.43%	23.43%
Expedited	60	1.2	21.18%	39.74%	39.74%
Passenger	79	1.2	27.22%	27.22%	27.22%
Freight	60	2.5	45.89%	45.89%	45.89%
Expedited	60	2.5	33.09%	37.32%	40.48%
Passenger	79	2.5	29.71%	34.79%	38.59%
Freight	60	4.5	41.72%	43.80%	45.34%
Expedited	60	4.5	39.66%	42.25%	44.18%
Passenger	79	4.5	37.15%	40.37%	42.77%
Freight	49	1.2	32.66%	32.66%	32.66%
Expedited	49	1.2	23.68%	30.27%	35.19%
Passenger	59	1.2	20.36%	27.78%	42.01%
Freight	49	2.5	38.59%	55.64%	55.64%
Expedited	49	2.5	35.27%	38.96%	41.71%
Passenger	59	2.5	32.93%	37.20%	40.39%
Freight	49	4.5	42.52%	44.39%	45.79%
Expedited	49	4.5	41.22%	43.42%	45.06%
Passenger	59	4.5	39.67%	42.25%	44.19%

A4. Conclusion

The analysis shows that significant reduction in train separation in following moves can be obtained with A-QMB when compared to B-QMB. Train separation reduction in A-QMB varied from 20.36 percent to 45.89 percent among different types of trains. Multiple factors affect the results, such as TC length, delays in the system, PTCEA rollup rates, train types, and MAS. Reduction in train separation can lead to gains in overall network capacity, particularly in territories with high train density operation.

The analysis also shows comparable train separation results between A-QMB and B-QMB with half TCs. The analysis indicates that heavier trains (i.e., freight trains) with longer braking curves have better train separation results in A-QMB when compared to B-QMB with half TCs, while lighter trains (i.e., passenger and expedited trains) have opposite effect.

Two enhancements are suggested to increase the capacity gains of A-QMB compared to B-QMB which are applying instant rollups for the leading train upon clearing the TC and applying an advanced TCs functionality that detect a leading train clearing a double-occupied block. Both enhancements increased the range of a freight train's case Min SSS gain up to approximately 55 percent.

The overall results indicate that implementing QMB with the NGTC and VRTL technologies can substantially reduce train separation and help increase railroad network efficiency, particularly in areas with dense traffic operation where following move operation is frequent.

Appendix A-1. Main Concepts in A-QMB

Close Following Move

A Close Following Move (CFM) occurs when two trains are on the same track, traveling in the same direction on the same route path, and are in close proximity of each other. This creates a need for the leading train to rollup its authority more often so that capacity is not wasted spatially between the leading train's PTCEA "From" limit and its rear position. CFM mode requires additional message traffic in the communication system due to more frequent PTCEA rollups and extensions as well as CFM mode activation/deactivation requests. Therefore, two different modes of operation are utilized for QMB rollup rates.

Non-CFM mode: used when CFM mode would not cause train headways to be significantly greater than otherwise necessary and attainable with normal train handling. While all QMB trains could always operate in CFM mode, this would consume significantly more wireless communications bandwidth than necessary. The purpose of having the two modes is to reduce bandwidth usage.

- For a baseline, it is assumed that PTCEA rollup occurs in an established frequency (e.g., every two minutes). This frequency could be based on the train's speed.
- Alternatively, PTCEA rollups may occur at events such as when the train clears a track circuit boundary or starts/stops.

CFM mode: used when non-CFM mode would cause train headways to be significantly greater than otherwise necessary and attainable with normal train handling.

Vital Rear-of-Train Location

VRTL is a location determination system that provides vital end-of-train location information to a train's locomotive, such as Positive Train Location End-of-Train (PTL-EOT). VRTL is an optional technology that can complement QMB operations. VRTL is necessary to achieve fail-safe collision protection at Restricted Speed. VRTL is also essential for achieving higher train separation gains in QMB alongside with NGTC.

Next Generation Track Circuit

Track circuits typically provide binary information for a fixed block. The conventional track circuit can either be clear (i.e., no occupancy and no broken rail) or not clear (i.e., occupancy and/or broken rail). The main concept of NGTC is to detect a broken rail with a shunting axle (occupancy) in the same block and to leverage wireless peer-to-peer communications infrastructure established for PTC. Refer to the NGTC ConOps and NGTC Requirements Specification document for more details.

Appendix A-2. Time Delays that Affect Margins in B-QMB and A-QMB

There are two distinct components that need to be considered in determining practically achievable train separation in B-QMB and A-QMB. One component is the safety margin that must be added to the end of a train “cleared location” reported in a rollup message, and the other component is the collective effect of all other items that contribute to train separation. The other items just affect operations (minimum achievable headway). The delays for each category are described below.

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 a VRTL system. Therefore, at the time of each PTCEA rollup, the onboard obtains from VRTL a high confidence estimate of the uncertainty (probably 6 or 7 sigma) for the current rear of train location report. 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 a stretching margin needs to account for that. The rear-of-train location uncertainty is added to the PTCEA rollup margin by the onboard.

Note that if VRTL is not in use and the onboard uses its train consist information to determine its rear-of-train location, there are several additional factors that need to be considered in determining the safety margin. These include head-of-train (HOT) location uncertainty and train length uncertainty.

b. Track Circuit and Wayside Interface Unit (WIU) Response Time

This time delay is based on coded track circuit pulse rates, which is in the range of a few seconds. This is in parallel with (not additive to) the other delays, so it will not affect train separation if it is less than the combined effect of the other contributors mentioned below. Therefore, this is a time delay that does not get added into the rollup margin.

This delay comes into play when the leading train clears a jointly occupied track circuit. The track circuit sends a pulse every 2.8 seconds in the case of conventional track circuits (as a baseline case). It could be up to 2.8 seconds before the next pulse comes along to verify that the NGTC is clear ahead of the following train. On average, this will result in 2.8 seconds/2 = 1.4 seconds of delay. This can be rounded up to 2 seconds to account for processing delays in the track circuit and WIU. Then it will be necessary to wait until the WIU’s F-frame timeslot comes around again before this status change can be transmitted in a Wayside Status Message (WSM). F-frame timeslots come around every 4 seconds, so this will result in a 2-second delay on average (not assuming worst case). The total delay would be 1.4 + 2.0 = 3.4 seconds on average. 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 acknowledgement scheme on WSMs. Similar to item d., Retransmission Time, it can be assumed that the WSM is not heard about 1 out of 10 times. This would add an average re-transmission time of 0.34 to the delay resulting in 3.8 seconds.

However, track circuit status does not affect PTCEAs, so it is not additive to the other delays. Therefore, it needs to be determined which is the greater delay (track circuits plus WIU response time or delays in the PTCEA update process) to determine minimum train separation, which in most cases will be less than the PTCEA update delays.

c. PTC Radio Superframe Length

The PTC 220 MHz radio is designed with a 4-second superframe size. When a message is to be sent over the radio, it will be sent in one time slot within the 4-seconds superframe. On average, this results in 2 seconds of delay for a message transmission. A "PTCEA update thread" includes all the message transactions that must occur between the time a PTCEA rollup message is sent from a leading train until the following train receives a PTCEA extension. The response to a message transmitted in one superframe can eventually occur in the same superframe, but in worst-case scenario, it will most likely occur in the subsequent superframe, i.e., a 4-second delay for each message transmitted. The following sequence of messages occur during a PTCEA update thread:

1. VRTL sends rear of train location to the head of train using message 1x.
2. Leading train (locomotive) sends a rollup to the office using message 1a.
3. Office sends updated PTCEA to the following train using message 2a.

According to the current system, a total of three 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.

This is a time delay that directly affects train separation, but it does not get added into the QMB rollup margin.

d. Retransmission Time

Re-transmission time is the delay added to message transmission when a radio message is not received on the first attempt (e.g., due to interference). When such events occur, the system has a mechanism to retransmit the message, in which the transmitter waits for an acknowledgement from the receiver, and if the acknowledgement is not received, 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., immediately after the transmission) and the retransmission is sent immediately after, i.e., in the next superframe. With these assumptions, if a retransmission occurs, it adds 6 seconds of delay (4 seconds for the not received acknowledgement plus 2 seconds to retransmit).

This analysis also assumes that 10 percent of the PTC220 MHz radio messages fail, i.e., require retransmission. The PTCEA update thread includes three messages as cited in item c. PTC Radio Superframe Length, and retransmission time was accounted for all of them. This is a time delay that directly and randomly affects train separation, but it does not get added into the rollup margin.

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 office and field. Based on feedback 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, but it does not get added into the rollup margin. This will vary from railroad to railroad. Most railroads have taken steps to minimize this delay to reduce 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 on average each processing stage takes 0.75 second averaged at each stage, namely:

- VRTL of leading train, to calculate rear-of-train position.
- Onboard of the leading train to process rear-of-train position and rollup its PTCEA.
- Office, to process PTCEA rollup of leading train.
- Office, to update and parse PTCEAs.
- Office, to create PTCEA extension of following train.
- Onboard of the following train.

With six stages of processing in the PTCEA update process, a total of 4.5 seconds is incurred. This is a time delay that directly affects train separation, but it does not get added into the rollup margin.

g. Time between PTCEA Rollups

When in CFM, the update rate between PTCEA rollups (nominally 16 seconds) adds to train separation. This is a time delay that directly affects train separation, but it does not get added into the rollup margin.

Appendix B. Hazard Analysis

B1. Introduction

The NGTC is an improvement upon conventional track circuits as the result of certain modifications. This new track circuit concept was developed to support QMB operation with the ability to detect a broken rail in an occupied block. With the combined functionality of NGTC, VRTL, and QMB, there are expected capacity gains in operation.

This report identifies potential hazards that might differ from those existing with conventional track circuits under PTC operation. The new or modified potential hazards identified are based on the concept of operation proposed for NGTC and QMB. This report also provides possible mitigations for the hazards identified. The risks and hazard mitigations are listed and evaluated based on their severity and probability.

B1.1 Scope

The scope of this initial safety analysis is to analyze the new or modified hazards brought into operation due to the NGTC upgrade. Hazards that do not differ in risk level for NGTC as compared with conventional track circuits are not in the scope of this analysis. The analysis includes hazards based on the conceptual design, system requirements, and proposed operations. An additional safety analysis needs to be performed as the system design is further specified.

Furthermore, assessment of NGTC failure modes cannot be performed until that hardware and software is designed. Therefore, these failure modes are not in this scope of this analysis.

B1.2 Background and Changes Compared to Conventional Track Circuits in Overlay PTC System

A track circuit is an electrical circuit that includes rails in order to provide track occupancy information and broken rail detection for the train control system. The NGTC system offers an upgrade to conventional direct current (DC) coded track circuits.

The conventional DC relay track circuit (an example is shown in Figure B1) has several major components, including a power supply, track relay, resistors, insulted joints, cables, and others. Those components can be divided into two major groups – the feeding side (i.e., transmit side) and receiving side. The feeding side normally contains the power supply (battery or other steady power resources) and track limit resistors which protect the circuit. The receiving side normally contains the track relay which contacts other signal devices in a fail-safe manner and a relay adjustment resistor which provides better shunting ability. When the train is shunting the rail or there is an open circuit, the relay is de-energized to indicate there is an occupancy or other issue in the track block.

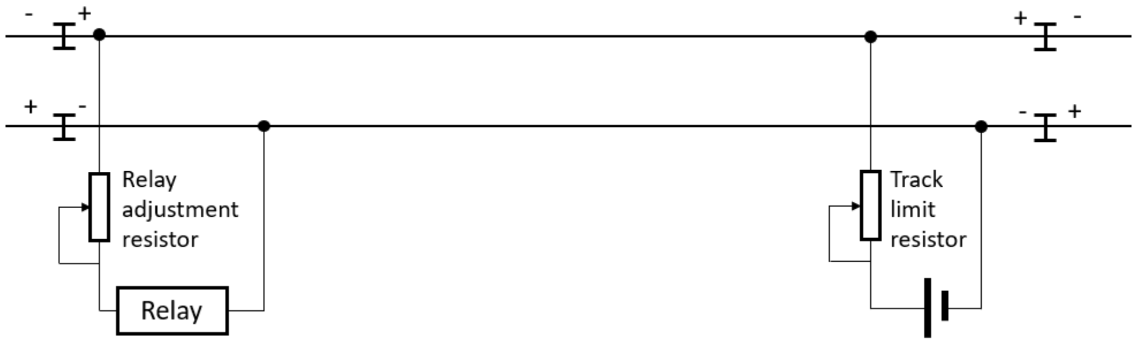

Figure B1. Conventional track circuit sample

With technology improvements and the increasing demands from train operations, especially with PTC deployment, the conventional DC track circuit has been widely replaced with coded track circuits, which provide better sensitivity and more functionality. A code transmitter (or transceiver) and code receiver (or transceiver) are added to the system, and the DC pulse code with information is sent through the circuit.

The NGTC system provides the ability to detect a rail break when the block is shunted by an occupancy. This new feature can be used by the QMB train control system to allow a following train to enter the same block at MAS if the rear of train location of the leading train is known with high assurance to be past an authority rollup point. Some hazards related to this upgrade are discussed in this report.

There are some characteristics shared between conventional track circuits and NGTC that may create hazards in operation. These include partial broken rails that do not create an electrical discontinuity, the current leakage through the ballast in wet or other condition, and the rusty surface or other situation that affect shunting sensitivity. Some of these are also being analyzed to see if the risk changes as a shared characteristic between conventional track circuits and NGTC.

B2. NGTC Safety and Hazard Risk Assessment

This analysis is focused on hazards that are introduced with NGTC-VRTL-QMB operation as well as existing hazards from conventional track circuit systems that have changed or affect system operation and design requirements. The analysis is based on the high-level QMB and NGTC design. As with any system development, further analysis should be performed as development progresses, and the hazard analysis will be updated accordingly as a prototype or final product is developed and throughout the product life cycle.

This analysis addresses the NGTC wayside devices, QMB onboard system, and office functions related to NGTC. The QMB operation concept, speed control procedures, and speed targets set for PTCEA are also taken into consideration.

Following the standard hazard analysis approach, this analysis was performed from three perspectives: Preliminary Hazard Analysis (PHA), System Hazard Analysis (SHA), and Operation and Support Hazard Analysis (O&SHA).

B2.1 Preliminary Hazard Analysis (PHA)

The purpose of a PHA is to identify hazards, assess their potential severity, and identify potential hazard mitigations before the system has been designed or before the system design is complete.

In the PHA task, an initial safety assessment of a concept or system is performed and documented. Based on the best available data, including mishap data (if accessible) from similar systems and other lessons learned, potential hazards associated with the proposed functions are evaluated for severity and operational constraints. Potential mitigations and alternatives to eliminate hazards or reduce their associated risk to an acceptable level are identified.

B2.2 System Hazard Analysis (SHA)

The SHA addresses hazards related to safety-critical functions to be implemented in subsystems. It identifies the hazards in more detail than the PHA, assigns each hazard to one or more subsystems, identifies the planned design mitigations (typically selected from candidate mitigations identified during the PHA), provides assessments of the risk associated with the hazards (this includes mitigations proposed for NGTC compared to conventional track circuits), and estimates residual hazard frequency or probability for use in the Hazard Risk Index (HRI – see Section B2.5). The term "residual" refers to the probability or risk after the planned mitigation(s) has been applied.

In the SHA, the residual Hazard Risk Assessment (HRA) is performed based on the severity assigned to each hazard in the PHA and the probability or frequency of that hazard after mitigations to be implemented by subsystem design. The objective of the HRA is to achieve a residual risk for each hazard that is both acceptable and achievable with the proposed implementation. HRA is based on HRI.

B2.3 Operation and Support Hazard Analysis

The purpose of the O&SHA is to identify and assess hazards introduced by operational and support activities and procedures, as well as to evaluate the adequacy of operational and support procedures, facilities, processes, training, and equipment used or proposed to be used to mitigate risks associated with identified hazards.

The O&SHA task builds on the SHA. The O&SHA identifies the methods planned to mitigate hazards that could not be eliminated by system design. The human is considered an element of the total system, receiving both inputs and initiating outputs within the analysis.

Like the SHA, the O&SHA identifies the hazards in more detail than the PHA, estimating residual hazard frequency or probability necessary to complete the HRA. Rather than specifying design features to be implemented, however, the O&SHA specifies operational and support procedures, facilities, processes, training, and equipment required and/or planned to adequately mitigate hazards.

Collectively, the SHA and O&SHA specify the mitigations (at a high level) chosen to adequately mitigate all identified hazards, thus achieving an acceptable level of risk. The mitigations flow down to detailed requirements in the NGTC segment specification.

B2.4 Hazard Risk Assessment

Section B3 shows the HRA, which combines the results of all three safety analyses performed, namely, PHA, SHA, and O&SHA. The residual risk level assessments shown in Section B3 are based on the collective effects of mitigations to be implemented by system (hardware or software) design (results of the SHA) and mitigations to be performed by humans (results of the O&SHA).

B2.5 Hazard Risk Index

Acceptable target safety levels have been defined by railroads implementing PTC. The HRI is a tool widely used to establish a required level of integrity based on the predicted probability and severity of identified hazards. The matrix in Figure B2 shows the HRI used for this analysis of QMB from the I-ETMS PTC Development Plan (PTCDP).[3]

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[3] Wabtec Railway Electronics, Union Pacific Railroad, Norfolk Southern Railway, CSX Transportation, Inc., Interoperable Electronic Train Management System (I-ETMS) Positive Train Control Development Plan (PTCDP) Version 2.0, 2011.

Severity → / Probability ↓	I Catastrophic	II Critical	III Marginal	IV Negligible
A Frequent	UN	UN	UN	AC
B Probable	UN	UN	UN	AC
C Occasional	UN	UN	AC/WR	AC
D Remote	UN	AC/WR	AC	AC
E Improbable	AC/WR	AC	AC	AC

Integrity Goal Definitions :

UN	- Unacceptable
AC/WR	- Acceptable with review by the railroad's chief safety officer or designated representative
AC	- Acceptable without review

Figure B2. Hazard Risk Index

The HRI correlates the predicted severity and probability of occurrence of identified hazards to a risk integrity goal. The matrix is used in the HRA process to establish initial hazard risk and to set priorities for resolutions that eliminate, minimize, or control the identified hazards. HRA is the process of combining the hazard severity and hazard probability to determine which identified hazards are:

- Acceptable as is (without officer review)
- Acceptable with review by the railroad's chief safety officer or designated representative and proper documentation thereof
- Unacceptable

Hazard assessment is based on the potential impact of the hazard on personnel, facilities, equipment, operations, the public, or the environment, as well as on the product itself. Other factors specific to the product may also be used to assess risk. For a vital overlay PTC system, Federal Regulations [4] mandate that sufficient documentation demonstrates that the PTC system, as built, fulfills the Safety Assurance Criteria and Processes set forth [5]. If an identified hazard cannot be eliminated, the process is to reduce the associated risk to an acceptable level through design and proper implementation using safety assurance concepts. The criteria used to assess each hazard's Severity and its Probability are defined in the following paragraphs.

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[4] "Positive Train Control Systems," Code of Federal Regulations, Title 49, Part 236, Subpart I, 2011

[5] "Safety Assurance Criteria and Processes," in Code of Federal Regulations, Title 49, Part 236, Appendix C, 2011

Hazard severity is defined as a qualitative measure of the worst credible mishap resulting from personnel error, environmental conditions, design inadequacies, and/or procedural deficiencies for a system, subsystem, or component failure or malfunction, and is categorized as follows:

I. Catastrophic
   - Deaths, system loss, or severe environmental damage

II. Critical
   - Severe injury, severe occupational illness, or major system or environmental damage

III. Marginal
   - Minor injury, minor occupational illness, or minor system or environmental damage

IV. Negligible
   - Less than a minor injury, occupational illness, or less than a minor system or environmental damage

Hazard probability is defined as the probability with which a specific hazard will occur during the planned lifecycle of the system element, subsystem, or component. Hazard probability can be described subjectively in potential occurrences per unit of time, events, population, items, or activity, and is ranked as follows, where P(incident) means probability of the incident:

A. Frequent
   - P(incident) > 1E-3 per operating hour
   - Classification associated with a hazardous event that is likely to occur often in the life of the system, subsystem, or component.
   - Likely to occur frequently in an individual item; may be continuously experienced in fleet/inventory.

B. Probable
   - 1E-3 per operating hour ≥ P(incident) > 1E-5 per operating hour
   - Classification associated with a hazardous event that will occur several times in the life of the system, subsystem, or component.
   - Will occur several times in the life of an item; will occur frequently in fleet/inventory.

C. Occasional
   - 1E-5 per operating hour ≥ P(incident) > 1E-7 per operating hour
   - Classification associated with a hazardous event that is likely to occur sometime in the life of the system, subsystem, or component.
   - Likely to occur sometime in the life of an item; will occur several times in fleet/inventory.

D. Remote
   - 1E-7 per operating hour ≥ P(incident) > 1E-9 per operating hour

- Classification associated with a hazardous event that is unlikely, but possible to occur in the life of the system, subsystem, or component.
- Unlikely but possible to occur in the life of an item; unlikely but can be expected to occur in fleet/inventory.

E. Improbable

- P(incident) ≤ 1E-9 per operating hour
- Classification associated with a hazardous event that is so unlikely to occur that it can be assumed it will not be experienced in the life of the system, subsystem, or component.
- Very unlikely; it can be assumed occurrence may not be experienced; unlikely to occur, but possible in fleet/inventory.
- The E (Improbable) category is not interpreted as zero probability; thus, zero risk. The E (Improbable) category includes all items that are judged to have a low or extremely low probability of occurrence. There is no zero-probability category included in the ranking matrix.

Each hazard is rated for risk (Severity-Probability) as I-E, II-E, etc., in Section B3. Where the information was available, a probability rating (A-E) has been qualitatively included in each item. Since the risk assessment ratings for conventional track circuits were not available, they are not shown in the table.

B3. Results of Hazard Analysis

The results of this hazard analysis are categorized into different hazard groups, described and listed in Table B1.

Table B1. Hazard group list

Group No.	Hazard Description
1	Spontaneous rail break
2	No distinction of single vs. multiple rail breaks
3	Rollouts
4	Broken wire
5	Insulated joint malfunction
6	Undetected rail defect/partial broken rail

The details of each group and items contained for each hazard group are fully addressed in the following subsections. Note that a fundamental requirement and assumption is that NGTC is designed to be fail-safe. Therefore, all failures of NGTC equipment can be assumed to have an acceptable risk level. Similarly, functionality implemented in the onboard and office that are involved in protecting trains using information provided by NGTC are similarly assumed to have fail-safe implementations.

This part of the report shows the detail for each hazard group along with scenarios explained in notes. The format of each item is shown as follows:

<table>
<tr><th colspan="5">Preliminary (PHA)</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
<tr><th colspan="5">System Hazard Analysis (SHA) & Operation and Support Hazard Analysis (O&SHA)</th></tr>
<tr><td></td><td></td><td></td><td></td><td></td></tr>
</table>

Note: This presents further details or explanation.

Abbreviations used in the assessment:

BR = broken rail
EOT = end of train
ES = entry side (end) of track circuit
HOT = head of train
IJ = insulated joint
RSR = restricted speed restriction
Rx = receive
Tx = transmit
XS = exit side (end) of track circuit

B3.1 Hazard Group (type of event): Spontaneous Rail Break

A spontaneous rail break is one that can occur at any time and is not caused by a train. This is a rare event.

B3.1.1 Condition: No occupancy

Note: The Tx and Rx signal for both sides of the track circuit will show the status 0. In this scenario, the current system design cannot identify the difference between broken wire and broken rail. This is not a safety concern, however, because a RSR will be applied in either case. The RSR protection will be required for the whole block and cannot be removed as long as the train occupies the block.

B3.1.2 Condition: BR location between XS boundary and HOT

Table B2. Analysis for B3.1.2 Condition

Hazard Description	Potential Hazard effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Spontaneous rail break (BR location between XS boundary and HOT)	1. Derailment	1. Potential lost warning when train rolls over BR location.	Catastrophic (I)	1. Once a BR is detected in front of the train, RSR is enforced for whole block, including for a subsequent train, at least until train is no longer passing over the break, possibly until train leaves the block.
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1	Wayside/ Onboard	Same or better than current PTC with conventional track circuits.	Improbable (E)	Acceptable with review (AC/WR)

Note: The key issue for this scenario is that when a BR is detected from the XS, the Tx signal will resume high status while the train is rolling over the BR location.

In Figure B3, a spontaneous rail break occurred after a train entered the block. The BR is detected by XS NGTC unit, as indicated by the low status of its Tx signal. The ES NGTC allows normal operation, as it shows an occupancy with no BR.

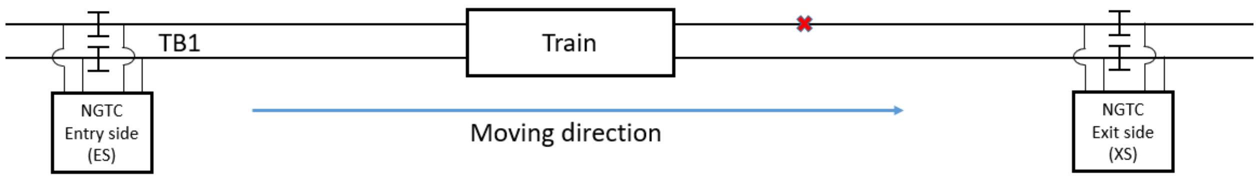

Figure B3 Rail break occurs in front of moving train, after train entered block

In Figure B4, while the train is rolling over the spontaneous rail break location, the Tx signal from the XS NGTC unit will resume high status as its wheels are shunting the track and closing a circuit loop for the signal measurement. If no other methods are taken to prevent this hazard, the NGTC XS unit will have a potential risk of indicating occupied status instead of BR status.

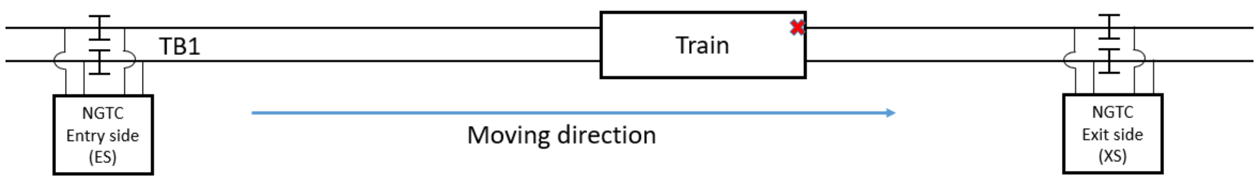

Figure B4. Moving train HOT rolls over BR location

In Figure B5, when the end of the train passes the spontaneous rail break location, the Tx signal from ES will drop to low, causing BR status to be indicated from the ES.

After the train is clear of this block, the Tx signal for both sides will be low, indicating BR status.

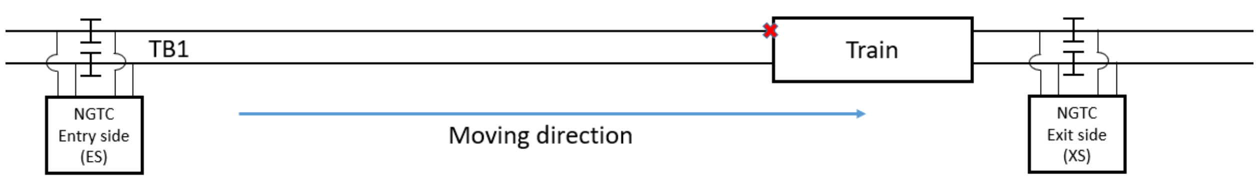

Figure B5. Moving train EOT rolls over BR location

B3.1.3 Condition: BR location between ES boundary and EOT

Note: The BR location between ES boundary and EOT is the hazard that the NGTC system is especially designed to detect what is not detected by conventional track circuits. As a rail break is detected behind the train, it will not affect the operation of that train, but all following trains will enter the block under RSR and lock (maintain) the RSR limitation for the whole block, because there is no indication of the specific location of the rail break nor whether additional rail breaks occurred after the initial one. There is a possibility that the following train will not be able to slow down enough by the time it passes the detected broken rail due to the limited available time between detection and deceleration of the train. However, the train crew will be notified about the broken rail, which is added safety beyond conventional track circuits.

B3.1.4 Condition: BR location between trains, distance gap between trains is shorter than BR location to XS boundary

Table B3. Analysis for B3.1.4 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Spontaneous rail break (Distance between trains is shorter than BR location to XS boundary.)	1. Derailment	1. No information can be provided about BR location until following train EOT passes the BR location. 2. Potential lost warning (train quantity larger than two)	Catastrophic (I)	N/A
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
N/A	Wayside/ Onboard	Slightly higher risk than PTC with conventional track circuits due to higher speed	Improbable (E)	Acceptable with review (AC/WR)

Note: The key issue for this scenario is that when the BR initially occurred, the system cannot detect the BR immediately because the trains are creating shunts from both sides.

In Figure B6, the break rail occurred between the trains and cannot be detected. The broken rail is not immediately detected as seen in Figure B7. In Figure B8, when the end of the following train passes the BR location, the ES NGTC will detect the BR. Notice that if the train is short enough, the state of Figure B7 may not last long enough to be detected, in which case the reported state may directly jump from that of Figure B6 to Figure B8.

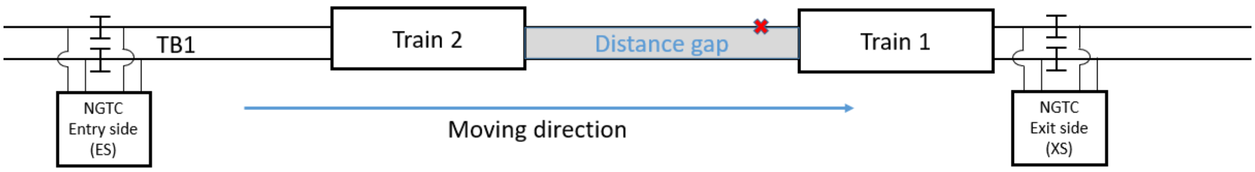

Figure B6. BR occurred between trains

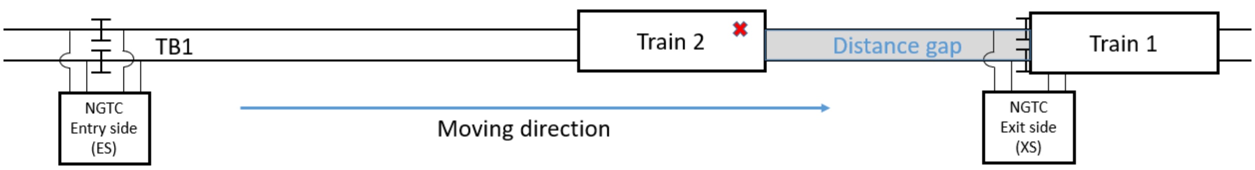

Figure B7. BR cannot be immediately detected

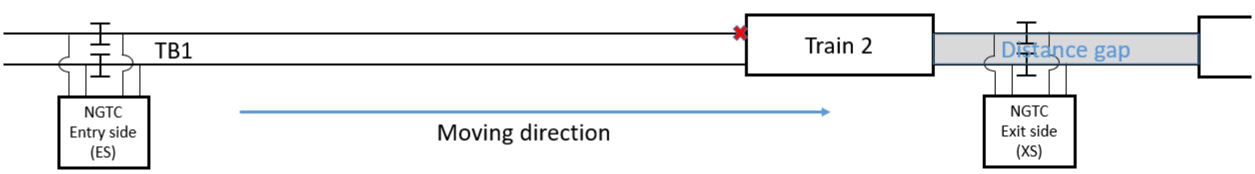

Figure B8. BR is detected when EOT rolls over the location

B3.1.5 Condition: BR location between trains, distance gap between trains is longer than BR location to XS boundary

Table B4. Analysis for B3.1.5 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Spontaneous rail break (Distance gap between trains is longer than BR location to XS boundary.)	1. Derailment	1. No information can be provided about BR until leading train clear of XS. 2. Potential lost warning (Tx signal of ES will resume to high when following train rolls over the BR location.)	Catastrophic (I)	1. When BR is detected by XS, all the trains in the block will be under RSR.

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1 and 2	Wayside/ Onboard	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

Note: In this scenario, the distance gap between trains is longer than the distance from the BR location to XS. When the leading train is clear of XS, the BR will be detected by the XS NGTC, and NGTC then reports the spontaneous rail break ahead of the following train.

In Figure B9, the rail break that occurred between the trains cannot be detected immediately. The broken rail is then detected as shown in Figure B10.

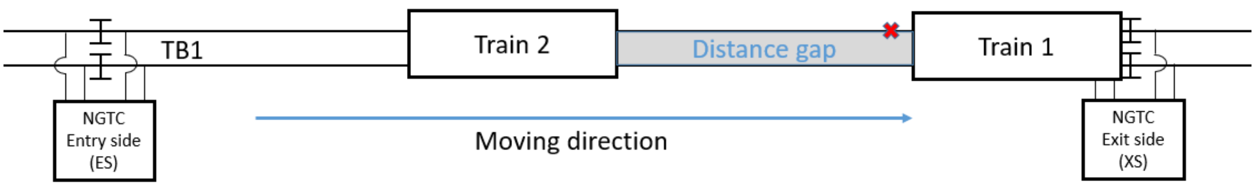

Figure B9. BR occurred between trains

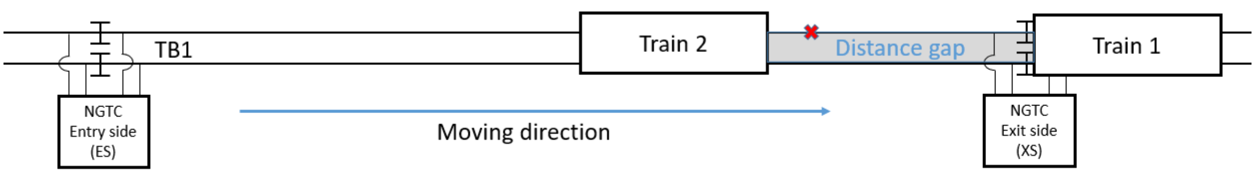

Figure B10. BR was detected once leading train clears the block

B3.2 Hazard Group (type of event): No Distinction Between Single versus Multiple Rail Breaks

B3.2.1 Condition: Multiple rail breaks in front of train

Note: NGTC does not indicate how many broken rails there are; instead, NGTC does provide indication there is at least one broken rail. The following train will enter the block under RSR.

B3.2.2 Condition: Multiple rail breaks behind train

Note: NGTC does not indicate how many broken rails there are; instead, NGTC does provide indication there is at least one broken rail. The following train will enter the block under RSR.

B3.2.3 Condition: Multiple rail breaks in front and behind train

Note: NGTC does not indicate how many broken rails there are; instead, NGTC does provide indication there is at least one broken rail. The following train will enter the block under RSR and the shunting vehicle between rail breaks cannot be detected.

B3.3 Hazard Group (type of event): Rollouts

In conventional track circuit systems, a rollout is protected with track circuit detection (e.g., an O/S) that affects a signal, a derail installed at the turnout, tying the switch point detector into the signaling system, and/or other safety methods. Nonetheless, a rollout at an unmonitored (hand-throw) switch without a derail or with a derail left in the wrong state is not protected by the train control system (whether the track circuit is conventional or NGTC) if the block is otherwise occupied.

The main difference between QMB-NGTC-VRTL operation and previous train control systems is that the NGTC potentially allows higher speed entry into an occupied block. If no mitigation methods are taken, the probability of collision at a hand-throw switch where NGTC is installed is slightly greater than with conventional track circuits, since in the latter case, crews should be watching for obstructions with enough time to stop safely per RSR. Severity of collisions in this NGTC scenario can be greater than with conventional track circuits, since the speed when a collision occurs can potentially be higher.

The rollout scenario analysis in this research is highly related to operation with PTCEAs when in a Close Following Move. If a block is only related to one active PTCEA, this block is considered a "Full PTCEA Covered Block"; if a block is not fully covered by a PTCEA (e.g., two PTCEAs within same block or a partial PTCEA covering the block), this block is considered a "Non-fully PTCEA Covered Block."

In Figure B11, Track Block 3 (TB3) for Train 2 is considered a non-fully PTCEA covered block, involving the PTCEA from leading Train 2 and following Train 1. If following Train 1 enters the block while Train 2 is still in the block, a rollout that subsequently occurs between them cannot be detected by NGTC (without mitigation).

In Figure B11, Track Block 2 is considered a full PTCEA covered block. If the NGTC detects any occupancy before Train 1 enters the block, the onboard will notice the conflict in PTCEA since Train 1 has not yet entered the block and will enforce an RSR for the whole block.

In Figure B11, the track block in which Train 1 is currently located is also a full PTCEA covered block, but any rollout occurring after train entered the block cannot be detected without mitigations, so NGTC performs the same as a conventional track circuit in this scenario.

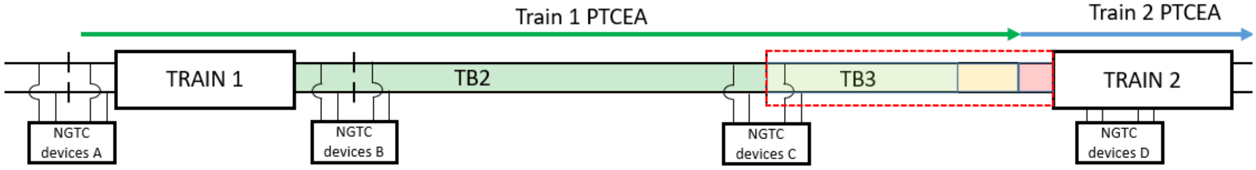

Figure B11. Full PTCEA and non-fully PTCEA covered blocks

B3.3.1 Condition: Rollout occurs in front of the train before train enters a full PTCEA covered block

Table B5. Analysis for B3.3.1 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs in front of the train before train enters a Full PTCEA Covered Block.	1. Collision	N/A	Catastrophic (I)	1. Apply the RSR for whole block if a conflict in PTCEA is detected.
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1	Wayside/ Onboard	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

B3.3.2 Condition: Rollout occurs in front of the train after train enters a full PTCEA covered block

Table B6. Analysis for B3.3.2 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs in front of the train after train enters a Full PTCEA Block.	1. Collision	N/A	Catastrophic (I)	1. Hi-rail vehicle could have QMB with PTL on board. 2. Auto-derail, derail position detector, or rollout detector suggested to be applied. 3. Onboard applies RSR at turnouts that are not protected by derail or detector. 4. PTCEA manager keeps record of derail operation based on

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
				information from crew (not fail-safe).
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
3	Wayside/ Onboard/ Office	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

B3.3.3 Condition Rollout occurs in a non-fully PTCEA covered block after leading train clears the block without updated PTCEA and following train has not yet entered the block

Table B7. Analysis for B.3.3.3 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs in a non-fully PTCEA covered block after leading train clears the block without updated PTCEA and following train has not yet entered the block.	1. Collision	N/A	Catastrophic (I)	1. If a clear status is indicated for a non-fully PTCEA covered Block, and then an occupancy status is indicated before following train enters the block, the RSR should be enforced for following train for the whole block.
Recommended Mitigation	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1	Wayside/ Onboard	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

Note: Once the leading train clears the block and a following train has not yet entered the block, the NGTC will send the clear status to the following train, if an occupancy status is sent later before the following train enters the block, the possibility of rollout should be considered and the onboard should enforce an RSR for the whole block.

B3.3.4 Condition: Rollout occurs from a siding without derail in a non-fully PTCEA covered block before leading train is clear of the block

Table B8. Analysis for B.3.3.4 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs from a siding without derail in a non-fully PTCEA covered Block before leading train clear of XS.	1. Collision	N/A	Catastrophic (I)	1. Onboard database check for derail installation. RSR for whole block if no derail installed.
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1	Wayside/ Onboard	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

Note: Wherever a derail or rollout detector (e.g., O/S) is not installed at the siding, the full potential of the NGTC cannot be performed, because rollouts may occur in an occupied block with non-fully PTCEA covered block.

B3.3.5 Condition: Rollout occurs after manual derail not restored in a non-fully PTCEA covered block before leading train clears the block

Table B9. Analysis for B.3.3.5 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs after derail not restored in a non-fully PTCEA covered Block before leading train clears the block.	1. Collision	N/A	Catastrophic (I)	1. Crew training related to the operation under new QMB-NGTC rules. 2. Auto-derail, derail position detector or rollout detector (e.g., O/S) suggested to be applied.
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1 and 2	Wayside/ Onboard	Probability of collision with rollout is slightly greater with NGTC than with conventional track circuits, since trains are operating slower per RSR with conventional track circuits (unlike with NGTC). Severity of collision with rollout can be greater with NGTC than with	Improbable (E)	Acceptable with review (AC/WR)

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
		conventional track circuits, since train can enter occupied block at MAS.		

B3.3.6 Condition: Rollout occurs due to crew operation errors and before leading train clears the block

Table B10. Analysis for B.3.3.6 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs due to crew operation errors and before leading train clears the block. Crew errors may include: - Train might exceed its PTCEA or might enter wrong track. - A train performing switching operations may exceed its limits and there is no enforcement.	1. Collision	N/A	Catastrophic (I)	1. Crew training related to the operation under new QMB-NGTC rules. 2. Enforce the switching train to stay within PTCEA limit (not in current QMB baseline due to operational issues).
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1	Wayside/ Onboard	Probability of collision with rollout is slightly greater with	Improbable (E)	Acceptable with review (AC/WR)

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
		NGTC than with conventional track circuits, since trains are operating slower per RSR with conventional track circuits (unlike with NGTC). Severity of collision with rollout can be greater with NGTC than with conventional track circuits, since train can enter occupied block at MAS.		

B3.3.7 Condition: Rollout occurs due to pull-apart from leading train

Table B11. Analysis for B.3.3.7 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs due to pull-apart from leading train.	1. Collision	N/A	Catastrophic (I)	1. VRTL is required on leading train in order for a following train to enter same

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
				block at MAS (already part of baseline system design).
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1	Wayside/ Onboard	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR), noting that risk is effectively eliminated with VRTL on the leading train.

B3.3.8 Condition: Rollout occurs due to unauthorized hi-rail vehicle or hi-rail vehicle in wrong track

Table B12. Analysis for B.3.3.8 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Rollout occurs due to unauthorized hi-rail vehicle or hi-rail vehicle in wrong track.	1. Collision	N/A	Catastrophic (I)	1. Require all hi-rail to be equipped with QMB with (HOT) PTL on board.
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1	Wayside/ Onboard	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR), noting the hazard is still subject to human error.

B3.4 Hazard Group (type of event): Broken Wire

This group is being analyzed to see if the risk changes compared to conventional track circuits.

B3.4.1 Condition: Broken wire when no occupancy

Note: A broken wire does not create a hazard because it would be detected and protected as a broken rail. Consequently, there is a reduction in operational capacity, but there should not be any safety issues. This hazard has the same implications (same risk level) as for current PTC with conventional track circuits. It is kept in the list since a broken wire is typically external to the track circuit equipment.

B3.4.2 Condition: Broken wire at ES

Note: A broken wire does not create a hazard because it would be detected and protected as a broken rail. Consequently, there is a reduction in operational capacity, but there should not be any safety issues. This hazard has the same implications (same risk level) as for current PTC with conventional track circuits. It is kept in the list since a broken wire is typically external to the track circuit equipment.

B3.4.3 Condition: Broken wire at XS

Note: A broken wire does not create a hazard because it would be detected and protected as a broken rail. Consequently, there is a reduction in operational capacity, but there should not be any safety issues. This hazard has the same implications (same risk level) as for current PTC with conventional track circuits. It is kept in the list since a broken wire is typically external to the track circuit equipment.

B3.5 Hazard Group (type of event): Insulated Joint (IJ) Malfunction

This group is being analyzed to see if the risk changes compared to conventional track circuits.

B3.5.1 Condition: Insulated joint worn out; resistance too low

Table B13. Analysis for B.3.5.1 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Insulated joint worn out, resistance too low	1. Derailment 2. Collision	1. Affect system from normal operation, affect shunt detection. 2. Misreading in signal measurement	Catastrophic (I)	1. Apply reverse polarity. 2. Apply different voltage output for adjacent block. 3. Apply different pulse clock cycle for adjacent block.
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1 and 3	Wayside	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

Note: Recommended mitigations were included in the NGTC requirements.

B3.5.2 Condition: Insulated joint temporary lost function, resistance too low

Table B14. Analysis for B.3.5.2 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Insulated joint temporary lost function, resistance too low.	1. Derailment 2. Collision	1. Affect system from normal operation, affect shunt detection. 2. Misreading in signal measurement	Catastrophic (I)	1. Apply reverse polarity. 2. Apply different voltage output for adjacent block. 3. Apply different pulse clock cycle for adjacent block.
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
1 and 3	Wayside	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

Note: Recommended mitigations were included in the NGTC requirements.

B3.6 Hazard Group (type of event): Undetected Rail Defect / Undetected Partial BR

This group is being analyzed to see if the risk changes compared to conventional track circuits.

B3.6.1 Condition: Undetected rail defect, full conductivity

Table B15. Analysis for B.3.6.1 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Undetected rail defect, full conductivity	1. Derailment	1.Potential same or low current reading for Tx and Rx	Catastrophic (I)	N/A
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
N/A	N/A	Same or better than current PTC	Improbable (E)	Acceptable with review (AC/WR)

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
		with conventional track circuits		

B3.6.2 Condition: Undetected rail defect, limited conductivity

Table B16. Analysis for B.3.6.2 Condition

Hazard Description	Potential Hazard Effect	Other Side Effect or Hazard Symptom	Severity Category	Potential Mitigation
Undetected BR, limited conductivity	1. Derailment	1.Potential same or low current reading for Tx and Rx	Catastrophic (I)	N/A
Recommended Mitigation(s)	**Subsystem or Person**	**Assessment**	**Residual Probability**	**Residual Risk**
N/A	N/A	Same or better than current PTC with conventional track circuits	Improbable (E)	Acceptable with review (AC/WR)

B4. Conclusion

The NGTC concept operated under the QMB system with VRTL provides multiple safety benefits, many achieved due to QMB and VRTL. If a complexity cost with the office can be accepted, more potential safety benefits can be applied, such as broken rail location identification, etc.

The key hazard identified during this initial hazard analysis is the rollout issue. Under QMB-VRTL-NGTC operation, a train can encounter certain rollout scenarios in which it enters an occupied block with higher speed than under conventional track circuits (which is the operational benefit of NGTC). The possibility of collision and severity of the collision is slightly increased, although this hazard still falls under the same hazard category [I-E].

The mitigations proposed in this analysis are based on QMB operational features and other possible methods and vary with the possible cause of the rollout. Some rollout scenarios can be mitigated or eliminated with the proposed mitigation methods, and some scenarios can only be controlled and occur at the same risk as conventional track circuit today due to the limitation of the system design. Some occur with slightly higher risk, as described in this document.

The mitigations proposed in this analysis have influenced the NGTC requirements and QMB requirements and are subject to change.

With the recommended mitigations and QMB-VRTL, all hazards investigated during the qualitative research are considered to have acceptable risk. The majority of hazards will have the same or lower risk under NGTC with QMB-VRTL.

Appendix C. Requirement Specification

C1. Background and Scope

This section provides the requirements for the NGTC subsystem. As a high-level requirements specification, it is intended to focus on user and functional requirements and not design and implementation details, which leaves the maximum possible flexibility for the supplier to develop the most effective design.

C1.1 Background

Currently, PTC is being implemented in the U.S. as required by the Rail Safety Improvement Act of 2008. Current PTC infrastructure integrates with conventional signaling systems and contains four segments that overlay the conventional signaling architecture: a locomotive onboard segment capable of automatic warning and enforcement of key signal aspects, civil speed restrictions, and mandatory directives; a back office segment that interfaces with railroad systems and provides data; a wayside segment that provides the status of wayside devices; and a wireless communications segment that connects the other segments.

The system most widely deployed to meet that mandate is ITC PTC. QMB is an enhancement to ITC PTC that has the potential to provide safety improvements and, in some implementations, performance improvements to the ITC overlay PTC system. The QMB concept can be applied to other PTC systems as well. QMB provides significant foundation for a subsequent upgrade to FMB train control.

Researchers conducted a research project funded by FRA to investigate an NGTC concept that could support higher capacity train control, such as QMB (basic or enhanced). Track circuits are considered a core component of the railroad signaling infrastructure, and it is beneficial to consider how they can be improved for operations, reliability, and lifecycle cost. This may be achieved by NGTC, due to the benefits it offers to QMB to support its operation and to increase traffic capacity and/or decrease lifecycle costs.

C1.2 Scope

This document specifies segment-level requirements for the NGTC subsystem. These requirements can help in supporting product development for NGTC. NGTC inherits conventional track circuits requirements for functions not stated in this document.

C1.3 Organization of the Specification and Requirements Designation

This document is organized according to the following sections:

- Background and Scope
- Reference Documents
- System Overview
- External interface Requirements
- Functional Requirements
- Performance Requirements
- Safety Requirements

- Extensibility Requirements
- Reliability, Availability, and Maintenance (RAM) Requirements

C2. Reference Documents

Table C1 lists the documents referenced in this specification. The NGTC Concept of Operations (ConOps) document is a companion to this specification as well as QMB Onboard System, Onboard Segment and Office Segment Requirements. It is recommended that the ConOps and QMB Requirements be read before or in conjunction with this specification.

Table C1. Referenced documents

NGTC Concept of Operations – part of NGTC final report
QMB System Requirements – not yet published
QMB Office Segment Specification – not yet published
QMB Onboard Segment Specification – not yet published
AAR S-9362.V1.1 Interoperable Train Control (ITC) Wayside-Locomotive Interface Control Document (ICD)
AAR MSRP S-9202 ITC Wayside Interface Unit Requirements

C3. System Overview

Conventional track circuits provide binary information for a fixed block. The track circuit can either be Clear (i.e., no occupancy and no broken rail) or Not Clear (i.e., occupancy and/or broken rail). Conventional track circuits cannot identify a rail break in an occupied block. The main concept of NGTC is to detect a broken rail with a shunting axle in the same block (in addition to what conventional track circuits detect) and to leverage wireless peer-to-peer communications infrastructure established for PTC. Additional key components of the concept presented in the CONOPS include:

- A broken rail is detected by monitoring the transmission current.
- All detections (i.e., occupancy, broken rail, or clear) only require binary decisions (not discernment of small differences in analog signal levels).
- Both transmitted current and received signals are monitored, and various combinations of transmitted currents and received signals are used to generate different statuses of NGTC. Signal reception is detected through voltage or current measurement.
- A movement authority concept is proposed to allow for a following train to enter an occupied detection block at MAS, thereby increasing the potential capacity, while still protecting the following train in the case of a broken rail between trains.

Figure C1 shows how a NGTC functions. Sources Tx2 and Tx3 transmit the signal and, depending on the voltage and current received at Rx2 and Rx3, occupancy and track integrity is determined (transmit current is also measured). Note that the received signal can be measured as voltage, current, or mechanically with a relay. Figure C2 shows the case where a single occupancy exists on the track.

Like conventional track circuits, NGTC cannot detect broken rail between two trains in an occupied block nor detect double occupancy of a block. However, authorized double occupancy can be identified through PTC exclusive authorities (PTCEA) limits when VRTL is functional.

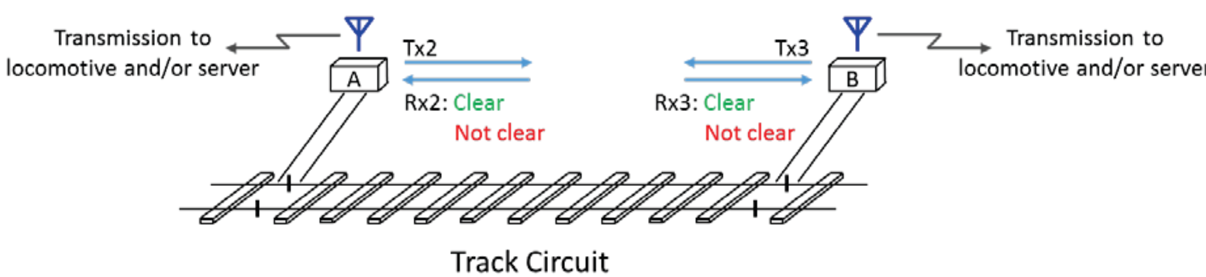

Figure C1. NGTC with interfaces for PTC

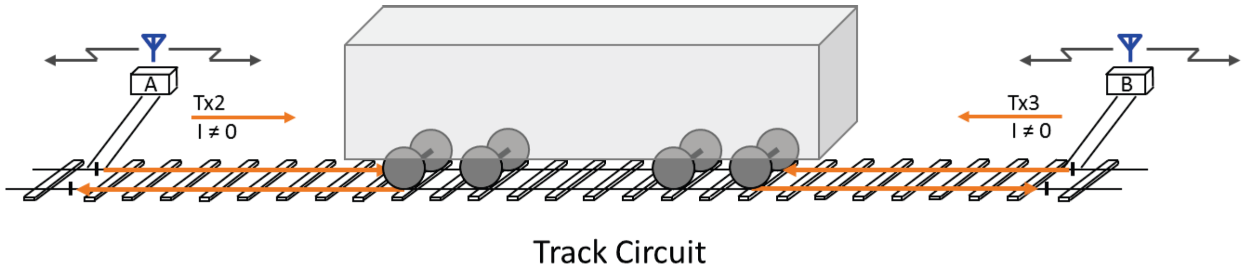

Figure C2. NGTC with transmitting current from both ends of a block

C3.1 NGTC Segment Requirements

C3.1.1 External Interface Requirements

a. Each NGTC installation shall interface with a wayside interface unit (WIU) to provide it with track circuit indications.
NOTE: The term "NGTC installation" is used here to refer to the electronics that perform NGTC functionality, located at a track circuit boundary, i.e., at an insulated joint.

C3.1.2 Functional Requirements

Detecting a rail break within an occupied block is achieved through the NGTC technology by measuring electrical current at the transmitting end. By combining the information from the transmission current ("Tx Current") and the received signal ("Rx Signal") that is based on transmission from the opposite end, four different track circuit states are possible, resulting in four different signal Device Status Code possibilities in wayside status messages (WSMs) for use by QMB trains. It is assumed there is time-coordination between both sides of the track circuit.

In addition, each WSM may also contain a different signal Device Status Code (with a different field offset) for use by a train that has PTC onboard with software that has not yet been upgraded to include QMB mode.

In addition to the four track circuit states, as with conventional track circuit WSMs, NGTC-based WSMs indicate whether a switch state is normal, reverse, or indeterminate.

The functional requirements of NGTC are:

a. NGTC shall measure the electrical current at the transmission end of the track circuit.
b. NGTC shall provide a binary indication of current presence by comparing the measured transmission current against a threshold value.
c. NGTC shall measure the electrical signal received at the end of the track circuit opposite from the transmitting end.
NOTE: The received signal may be measured in terms of voltage or current.
d. NGTC shall provide a binary indication of received signal presence by comparing the signal received at the end of the track circuit opposite from the transmitting end against a threshold value.

e. NGTC shall aggregate binary information from the measured transmission current ("Tx Current") and the received signal ("Rx Signal") that is based on transmission from the opposite end of the track circuit, to provide one of the following possible indications:

- Tx Current = Zero; Rx Signal = Zero
- Tx Current = Zero; Rx Signal = Substantial
- Tx Current = Substantial; Rx Signal = Zero
- Tx Current = Substantial; Rx Signal = Substantial

  Note: "Zero" means a value that is small and not much greater than zero (i.e., below a threshold). Substantial means a value that is substantially greater than zero (i.e., exceeds the threshold).

f. NGTC shall provide the indications to the WIU for use in WSMs that are shown in Table C2, hereafter referred to as "NGTC-based WSMs."

Note: NGTC could use the same WSM format defined in AAR S-9362.V1.1, while transmitting two different Device Status Codes, each with its own field offset, one for use by QMB trains and the other for EO-PTC trains.

Table C2. NGTC states for binary detected signals and indications of NGTC-based WSMs

Tx Current	Rx Signal	Meaning	NGTC WIU Indication	EO-PTC Indication	QMB Indication
0	0	Broken rail, either in unoccupied block or between Tx and shunting axle	Restricted	0	0,0
0	1	Not physically possible and this would indicate an NGTC failure.	NGTC is inoperable (Restricted).	0	0,1
1	0	• Occupancy somewhere in block • No broken rail between Tx and shunting axle • Can enter at MAS	Clear to proceed at MAS if train ahead has functioning VRTL.	0	1,0*
1	1	Clear	Clear to proceed at MAS	1	1,1

*In the case that a PTCEA extends through the entire block, this would indicate a rollout or another anomaly when in this state.

g. For a given track circuit boundary, NGTC shall produce indications for each adjacent track circuit.

NOTE: i.e., NGTC will produce an indication for track circuit 1 on the north or west side of the WIU, and another WSM for track circuit 2 on the south or east side of the WIU.

h. NGTC shall use pulsed DC signals for detecting occupancies and rail breaks.

i. NGTC shall coordinate pulse timing to avoid interference in track circuit signals between each end of the track circuit.

j. NGTC shall be able to save logs of track circuit statuses.

C3.1.3 Performance Requirements

a. NGTC shall detect a 0.06 ohm shunt.

b. NGTC shall report track circuit status at least once every second.

C3.1.4 Safety Requirements

a. NGTC shall be implemented as a fail-safe system.

b. NGTC shall detect its failures and send WSMs conveying the failure status.

Note: Being a fail-safe system, there are different ways that NGTC can convey a fail status, e.g., by transmitting a health status bit, by transmitting the 0,1 QMB state, by indicating the most restrictive state, or by transmitting nothing.

C3.1.5 Extensibility Requirements

There are no requirements related to this section.

C3.1.6 RAM requirements

a. NGTC shall comply with Section 3.7.6 of AAR MSRP S-9202.