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Federal Railroad Administration

Positive Train Location End-of-Train Final Report

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Final Report
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13. ABSTRACT (Maximum 200 words) The overall goal of the Positive Train Location (PTL) end-of-train (EOT) project was to build on the successes of the PTL Phase II project and further refine the use cases, review/modify PTL EOT segment requirements, and identify a path forward for addressing technical issues from the previous phase. Refined use cases and modified segment requirements facilitated the development of a functional PTL EOT segment that can operate in the on-track railroad environment in which it was intended to function. An analysis was conducted based on information surveyed from the Technical Advisory Group (TAG) to weigh options of operational need, segment performance, and overall PTL EOT segment unit price. The biggest driving operational need is to provide high confidence EOT positioning performance that enables secure and cost-effective fulfillment of the operational use cases identified. The PTL EOT segment will remain compatible with the head-of-train device (HOTD) segment specifications identified in the Association of American Railroads' (AAR) Manual of Standards and Recommendations Practices (MSRP) Section K-2, Standard S-9103 "Precision Navigation Module."			
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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

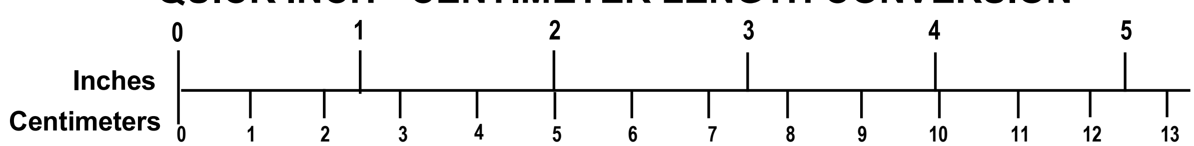
VOLUME (APPROXIMATE)

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

°F	-40°	-22°	-4°	14°	32°	50°	68°	86°	104°	122°	140°	158°	176°	194°	212°
°C	-40°	-30°	-20°	-10°	0°	10°	20°	30°	40°	50°	60°	70°	80°	90°	100°

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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Name	Organization
• Patrick Baker	ARRC[1]
• George Newman	ARRC
• Eric Hullemeyer	NS[2]
• Josh Allison	NS
• Lewis Ray	NS
• Steven Mazurski	BRC[3]
• John Spero	BNSF[4]
• Jim Barrett	BNSF
• Ed Tilley	BNSF
• Kevin Stokes	CSX[5]
• Robert Jenkins	CSX
• Roy Carter	CSX
• Mike Dizor	CSX
• Dan Fitzgerald	UP[6]
• Joe Drapa	UP
• Mike Newcomb	UP
• Dan Rubin	UP
• Gleb Geguine	CN[7]
• Alain Gagné	CN
• Luc Dumontier	CN
• David Thurston	CP[8]
• Jeff Switzer	CP

[1] Alaska Railroad (ARRC)

[2] Norfolk Southern Railway (NS)

[3] Belt Railroad Company of Chicago (BRC)

[4] Burlington Northern Santa Fe Railway (BNSF)

[5] CSX Corporation (CSX)

[6] Union Pacific Railroad (UP)

[7] Canadian National Railway (CN)

[8] Canadian Pacific Railway (CP)

Name	Organization
• Doug Vogl	KCS[9]
• Rick Stones	KCS
• Sanjiv Kamat	KCS
• Nathan Brown	KCS
• Brian Parr	KCS
• Melody Sheahan	AAR
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• Clark Palmer	Meteorcomm
• Noel Coward	Herzog
• Jared Withers	FRA[10]
• Shon Sloat	Leidos
• Armando Stettner	Meteorcomm

[9] Kansas City Southern Railway (KCS)

[10] Federal Railroad Administration (FRA)

Contents

Executive Summary

The Federal Railroad Administration sponsored Transportation Technology Center, Inc. (TTCI) to identify the necessary capabilities for the end-of-train (EOT) segment of a Positive Train Location (PTL) system. With the support of a Technical Advisory Group (TAG) composed of representatives from the North American railroad industry, the segments were used to select an architecture and establish updated requirements for the PTL EOT segment. The research took place from September 17, 2018, to September 16, 2019, at the Transportation Technology Center (TTC) in Pueblo, CO.

Most Positive Train Control (PTC) systems rely on Global Positioning System (GPS)-based location determination systems, which generally are not sufficient for track discrimination or determination of train length for train control purposes. The goal of the original PTL project was to develop a system that could determine the position of the front of the train and the rear of the train to an accuracy of less than 1.2 meters, at a confidence level of 99.999999997% (10 nines) in order to determine train length and track discrimination. While this accuracy was attainable at the Head-of-Train (HOT), this performance could not generally be achieved at the EOT.

The constraints imposed by the original accuracy requirements for the PTL EOT segment drove the design of a high-cost system that was still unable to meet all the performance requirements. It was determined that the use cases used to derive the segment requirements, and the requirements themselves, needed to be re-evaluated to validate their importance to the railroads. With feedback from the TAG, TTCI determined which key use cases drive accuracy requirements in order to derive a more relevant set of PTL EOT segment requirements.

The following are key results and recommendations from the PTL EOT project:

- Use cases were produced and evaluated with the TAG to establish railroad operations and scenarios that would drive requirements for the PTL EOT segment. These use cases ranged from standard railroad operations where determining the position of the EOT is required, to operating exceptions such as emergency brake applications and component failures. Necessary capabilities of the PTL system were identified from these use cases, which required leveraging the PTL EOT segment.
- Multiple PTL EOT segment architectures were proposed to support the capabilities identified with varying degrees of accuracy. With agreement from the TAG, it was determined which architecture was the minimum required to support each capability in its associated use case. This evaluation was used to select an architecture with the TAG from which to base performance requirements of the PTL EOT segment.
- Requirements from the previous phase of the project were revisited and evaluated against the established capabilities and the selected architecture to determine their validity and identify deficiencies. This requirements list was modified and expanded to produce a final set of requirements defining a PTL EOT segment capable of supporting the updated use cases and with the performance capabilities defined by the TAG-selected architecture.

1. Introduction

The Federal Railroad Administration (FRA) sponsored Transportation Technology Center, Inc. (TTCI) to review and modify operating scenarios and segment requirements related to the end-of-train (EOT) segment of the Positive Train Location (PTL) system. This document describes the work performed, analysis, and recommendations for a path forward for development and testing of a PTL EOT segment capable of meeting the existing and future needs of the railroad industry.

1.1 Background

Most Positive Train Control (PTC) systems rely on Global Positioning System (GPS)-based location determination systems to identify the location of the controlling locomotive of a train. The location of the rear of the train is then derived from the location of the locomotive using train length data; typically provided by the railroad's Management Information Systems (MIS) and confirmed or updated by the locomotive engineer. The MIS-provided train length is an approximation and is not considered to be reliable enough to independently determine the actual length of the train for safety-critical purposes. Train length can be critical data that needs to be dependable. Operating performance and safety can be affected if the PTC system is responsible for truncating or releasing movement authorities behind a train; for example, in dark (unsignaled) territory. Additionally, the current accuracy level of GPS-based location used by PTC systems is not sufficient to perform track level discrimination under certain conditions.

The PTL system was designed to provide head-of-train (HOT) and EOT location with sufficient resolution to discriminate track location in multiple track territory. In the initial development, many of the same requirements were applied to both the HOT and EOT segments without full consideration of the different operating environments in which each segment would need to perform. As a result, the EOT segment of the PTL system faced technical challenges during initial PTL development testing. These included:

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

1.2 Objectives

The objectives of this project were to:

- Refine the use cases based on existing and future railroad operating needs
- Review/modify PTL EOT system requirements that were developed in the previous FRA project to reflect train positioning needs of future operating environments and use cases
- Identify a path forward for facilitating the development of a practical PTL EOT device that will meet the requirements for the use cases in which it will be required to function

1.3 Overall Approach

TTCI conducted this project in cooperation with a Technical Advisory Group (TAG) consisting of railroads, technology experts, and FRA representatives. To achieve the stated objectives, TTCI performed the following:

- Reviewed the existing PTL EOT segment use cases and PTL EOT segment requirements
- Modified PTL EOT use cases to reflect current and future methods of train control
- Facilitated consensus with the TAG on PTL EOT segment use cases and capabilities
- Developed a standalone PTL EOT segment requirements document, including current and modified PTL system requirements
- Worked with the TAG and technology contractor to prepare a work plan and cost estimate to develop a working prototype PTL EOT device—based on the updated use cases and the segment-level requirements developed for the PTL EOT segment—for a potential follow-on phase of work

1.4 Scope

The following defines the scope of work:

- Assembling an industry TAG to provide input and review based on the technical issues that were identified during initial field testing of a PTL EOT system
- Working with the TAG on the following:
  - Reviewing and documenting use cases pertaining to the EOT segment
  - Reviewing the existing PTL system requirements to determine the applicability of each requirement to the EOT segment, based on the use cases identified
  - Developing and/or modifying segment-level requirements for a PTL EOT segment as necessary
    - All segment-level requirements will be open standard requirements and are not proprietary
  - Working with a technology developer to verify feasibility, develop a work plan, and develop associated cost estimate, outlining a path forward to address PTL EOT issues
  - Preparing a final report documenting the work performed, analysis, recommendations, results, and findings pertaining to a PTL EOT segment

The intent of this project was to review and modify existing documentation, develop segment-level requirements for the PTL EOT segment, and to provide suppliers with sufficient detail in the specifications to develop a prototype of a PTL EOT segment. Development, testing, and demonstration of these components was not included within the scope of this phase and may be conducted in a future follow-on-phase.

1.5 Organization of the Report

This report is organized into the following sections:

- Section 1 provides background information on the project.
- Section 2 provides overviews of the work performed.
- Section 3 provides overviews of the PTL EOT segment analysis.
- Section 4 provides overviews on recommendations for a path forward.
- Section 5 contains the conclusions derived from the analysis of the existing PTL EOT use cases and capabilities.
- Appendix A contains the use case summary
- Appendix B provides the use case capability matrix
- Appendix C contains a detailed analysis
- Appendix D provides the PTL EOT systems requirements document
- Appendix E contains estimated vendor costs for developing and testing a PTL EOT segment
- Appendix F describes a path moving forward

2. PTL EOT Use Cases and Requirements

This section provides a description of the use cases that were modified/developed for the PTL EOT segment to support existing and future methods of train control along with the associated capabilities and requirements needed to support these use cases.

2.1 Modify PTL EOT Segment Use Cases

Based on findings and technical challenges from the initial development of the PTL system, TTCI, with input from the TAG and FRA, determined that in many instances the use cases did not sufficiently differentiate operational needs between the HOT and EOT segments, which resulted in some onerous EOT segment requirements. Based on these findings, TTCI, with input from the TAG, developed use cases that were more specific to the EOT segment of the PTL system. The updated use cases and requirements support current and future rail operations, identify desired capabilities and characteristics of the PTL EOT segment, and document PTL EOT segment environmental constraints. TTCI provided the updated use cases to the TAG for their review and comment and gained agreement on the PTL EOT use cases. The complete list of updated PTL EOT segment use cases can be found in Appendix A.

Each use case is categorized by an operational scenario (denoted as OS below) which serves to facilitate separate evaluation of use cases that are the same but occur under different conditions (such as forward and reverse movement). Below is a summary list of the operational scenarios and associated use cases (denoted as UC below).

OS-01 – Forward Movement (HOT is lead-end of the train):

- **UC-1.1 – Non-Turnout Movement:**

  Variations: Tangent, curve, proximity to point of interest (POI) (clearing or approaching relevant track features, infrastructure, authority limit)

  Movement through territory other than switching and entering/leaving sidings, spurs, junctions, crossovers, or yards/terminals. Train is not part of a close-following move.

- **UC-1.2 – Facing Point Turnout Operations:**

  Variations: Yards/terminals, sidings, crossovers, junctions, spurs, separating (intentional), and coupling

  Railroad operations such as entering sidings, spurs, junctions, crossovers, yards/terminals, or switching

- **UC 1.3 – Trailing Point Turnout Operations:**

  Variations: Yards/terminals, sidings, crossovers, junctions, spurs, separating (intentional), and coupling

  Railroad operations such as leaving sidings, spurs, junctions, crossovers, yards/terminals, or switching

- **UC 1.4 – Close Following Moves (CFM):**

  Variations: Constant speed, accelerating, braking, grade

Train movements where the PTL train is being closely followed by another train. Excludes yard and siding operations.

- **UC 1.5 – Unintentional Train Separation:**

  Separation of the train not initiated by the train crew for railroad operations

- **UC 1.6 – Crew Initiated Emergency Brake Application:**

  Emergency brake application initiated by the train crew or PTC

- **UC 1.7 – EOT Reinitialization While in Motion:**

  The EOT segment reinitializes during train movement

- **UC 1.8 – EOT Component Failure:**

  A component of the EOT device ceases to operate correctly

- **UC 1.9 – EOT Communication Coverage Loss or Interference:**

  The EOT device loses communication with the HOT, or experiences degraded communication quality.

OS-02 – Reverse Movement (EOT is lead-end of the train):

- **UC-2.1 – Non-Turnout Movement:**

  Variations: Tangent, curve, proximity to POI (clearing, track features, infrastructure, authority limit)

  Movement through territory other than switching and entering/leaving sidings, spurs, junctions, crossovers, or yards/terminals. Train is not part of a close-following move.

- **UC-2.2 – Facing Point Turnout Operations:**

  Variations: Yard N/X, sidings, crossovers, junctions, spurs, entering/leaving siding, separating, and coupling

  Railroad operations such as entering sidings, spurs, junctions, crossovers, yards/terminals, or switching

- **UC-2.3 – Trailing Point Turnout Operations:**

  Variations: Yard N/X, Sidings, crossovers, junctions, spurs, entering/leaving siding, separating, and coupling

  Railroad operations such as leaving sidings, passing junctions, crossovers, or switching

- **UC-2.4 – Unintentional Train Separation:**

  Separation of the train not initiated by the train crew for railroad operations

- **UC-2.5 – Crew Initiated Emergency Brake Application:**

  Emergency brake application initiated by the train crew or PTC

- **UC-2.6 – EOT Reinitialization While in Motion:**

  The EOT segment reinitializes during train movement.

- **UC-2.7 – EOT Component Failure:**

  A component of the EOT device ceases to operate correctly.

- **UC-2.8 – EOT Communication Coverage Loss or Interference:**

  The EOT device loses communication with the HOT, or experiences degraded communication quality.

OS-03 – Stationary:

- **UC-3.1 – PTC System Initialization/Termination:**

  The PTC system initializes, aided by information from the PTL system

- **UC-3.2 – EOT Initialization/Termination:**

  The EOT segment initializes

- **UC-3.3 – Train is Idle:**

  Train is stopped and waiting (such as at a signal, or in a siding)

- **UC-3.4 – Unintentional Train Separation:**

  Separation of the train not initiated by the train crew for railroad operations

- **UC-3.5 – EOT Component Failure:**

  A component of the EOT device ceases to operate correctly.

- **UC-3.6 – EOT Communication Coverage Loss or Interference:**

  The EOT device loses communication with the HOT, or experiences degraded communication quality.

OS-05 – Off Track (EOT devices is not mounted on a train):

- **UC-4.1 – Inventory Monitoring:**

  Tracking location of an EOT device when not connected to a train and/or paired to an HOT. The device might not be near a track, so absolute coordinates must be reported.

Once the PTL EOT use cases were agreed upon, analysis of the operational scenarios indicated that the PTL system would require additional capabilities for both HOT and EOT segments to meet industry needs for recently defined future methods of operation that were not captured in the initial requirements developed for the PTL system.

2.1.1 PTL EOT Capabilities

The capabilities, and their associated definitions, for the PTL EOT segment include:

- **C-01a - Determine Relative Position of EOT Along Track and Proximity to POI:**

  Determine the position of the EOT along track based on railroad frames of reference when GNSS signals are available. Determine the position of EOT relative to POI such as clearance points of signals, switches, crossings, and other infrastructure. It is assumed that the EOT will *not* have access to a track database, so the determination of relative distance between the EOT and a POI will be done at the head of the train (either in the

PTC segment or the PTL HOT segment) where track data is available. The EOT will only contribute its location information to this relative distance determination process.

- **C-01b - Determine Relative Position of EOT Along Track and Proximity to POI after GNSS loss:**

  Determine the position of the EOT along track based on railroad frames of reference without GNSS position data. Determine the position of EOT relative to POI such as clearance points of signals, switches, crossings, and other infrastructure without GNSS position data.

- **C-02a - EOT Track Discrimination:**

  Identify which track the EOT occupies when near other (e.g., parallel) tracks when GNSS signals are available

- **C-02b - EOT Track Discrimination After GNSS Loss:**

  Identify which track the EOT occupies when near other tracks without GNSS position data

- **C-03a - Determine EOT Speed:**

  Determine the speed at which the EOT is moving when GNSS signals are available

- **C-03b - Determine EOT Speed After GNSS Loss:**

  Determine the speed at which the EOT is moving without GNSS position data

- **C-04a - Estimate EOT Position After Reinitialization While in Motion:**

  In the case of a re-initialization of the EOT while in motion, where the EOT position history is unknown, the PTL system determines EOT position. GNSS is required.

- **C-04b – Re-initialization While in Motion without GNSS for Conventional ETD Functions:**

  In the case of a reinitialization of the EOT while the train is in motion, where the EOT position history is unknown and GNSS is not available, the EOT retains basic ETD functionality.

- **C-05 - Estimate EOT Position Uncertainty and Confidence:**

  The PTL system estimates the uncertainty and level of confidence associated with position estimates; whether or not GNSS signals are available.

- **C-06 - Determine Train Integrity (EOT Brake Pipe Pressure (BPP), Train Length, Speed Delta):**

  The PTL system identifies when unintentional train separation has occurred

- **C-07 - Perform Closed Loop Emergency BPP Reduction at EOT:**

  The EOT initiates an emergency BPP reduction via the ETD using a closed-loop communications protocol with the HOT device.

- **C-08 - Determine EOT Segment Health:**

  The PTL system determines health of the EOT segment.

- **C-09 - Facilitate Diagnosis/Diagnose EOT Component Failures:**

  The PTL system identifies component failures when they occur, and provides an interface that facilitates the diagnosis of failures for railroad employees.

- **C-10 - Facilitate Replacement/Replace Failed EOT Components:**

  The PTL system facilitates replacement of failed components through both physical design (removal/connection of modular components) and software (interfacing with newly installed components).

- **C-11 - Graceful Degradation in the Event of PTL Component Failure:**

  The EOT gracefully returns to a minimum state of standard ETD functionality (or better) in the event of component failure.

- **C-12 - Pair/Unpairing EOT w/HOT:**

  The EOT pairs with the correct HOT device.

- **C-13 - Interface w/EOT Radio, ETD, and Locomotive Communications Manager:**

  The HOT portion of the PTL system interfaces with the communications manager device on board the locomotive used to manage communication among the onboard radios and onboard applications (including PTC). The locomotive crew interface with the PTL system is assumed to be via the onboard PTC user interface. The PTL EOT segment interfaces with the radios (railroad band and cellular) at the EOT and with the conventional end-of-train device (ETD) equipment, providing the necessary queuing and multiplexing to allow the PTL EOT and the ETD to share the same radio(s).

- **C-14 - Interface w/Operator:**

  The EOT provides an interface for operators and maintainers to perform basic configuration, self-test, and pairing functions at the ETD.

- **C-15 – Report General Location – Global Coordinates:**

  The EOT reports its global coordinates independent of railroad reference frames.

A complete use case and capabilities matrix is provided in Appendix B. Further explanation of the use case and capabilities matrix is provided in Section 3.

2.1.2 PTL HOT Additional Capabilities

Since the scope of this project was limited to the PTL EOT segment of the PTL system, the additional capabilities of the legacy HOT segment were identified but not analyzed in detail. In order to fully leverage the PTL EOT segment positioning performance and functional capabilities, the following PTL HOT segment capabilities may be necessary.

1. **Track database availability.**
   Parse subdivision files to extract track centerline and POI position information.
2. **PTL EOT segment navigation solution fusion of PTL EOT segment sensor data.**
   Maintain a separate PTL EOT segment navigation solution that incorporates PTL EOT segment sensor data, PTL HOT segment historical data, and track database.
3. **PTL EOT segment navigation solution incorporation of switch direction data.**

Maintain EOT track ID as the EOT moves through switches.

4. **PTL EOT segment navigation solution absolute position reset, based on PTL EOT segment POI detection.**
   Reset EOT position to the surveyed switch location identified in the track database.
5. **PTL EOT segment navigation solution absolute position update, based on PTL EOT segment POI relative distance.**
   Determine both EOT absolute position and EOT distance relative to PTL EOT segment-detected POI.
6. **HOT-to-EOT distance.**
   Maintain a continuous estimation of along-track train length between HOT and EOT.
7. **Back propagation-based EOT positioning.**
   For cases in which the HOT moves forward with the EOT trailing, maintain a moving history of its prior positions for at least one train length.
8. **HOT-to-EOT radio interface.**
   Provide ethernet access to an on-board HOT-to-EOT radio.
9. **Brake system message handling.**
   Receive PTL EOT segment radio messages and distinguish which are HOT purposed vs. which are brake management purposed.
10. **Adaptive communication channel.**
    Support changing radio communication channels and bands in the event of a radio communications failure.
11. **HOT-EOT pairing.**
    Allow for the autonomous pairing with the PTL EOT segment in the presence of other active PTL HOT and EOT segments that may be in the process of pairing.

2.2 PTL EOT Segment Requirements

Following the stated architecture developed in previous phases [1], results from previous PTL testing indicated that the performance requirements applied to the PTL EOT were not achievable with a GNSS-only solution. This is due primarily to the integration of PTL functionality into the existing ETD, which places the GNSS receiver antenna immediately behind the rearmost car. The placement of the antenna at this position causes constellation masking—up to half of available satellites can be obscured from the GNSS receiver antenna. Further analysis of data provided by Union Pacific Railroad supports the findings of constellation masking from previous PTL testing. The results of this analysis can be found in Appendix C.

Based on the use cases developed and discussed in Section 2.1, TTCI developed a standalone PTL EOT segment requirements specification by allocating existing PTL system requirements to the PTL EOT segment, modifying existing PTL EOT segment requirements, as necessary, and developing new requirements. The PTL EOT segment requirements specification is written with sufficient detail to develop a working implementation of a PTL EOT segment in a potential follow-on phase. The PTL EOT segment-level requirements specification includes both functional and performance requirements, including the following:

- PTL EOT segment communication requirements

- PTL EOT segment positioning accuracy requirements
- PTL EOT segment availability requirements
- Consist integration requirements

TTCI engaged the TAG to facilitate agreement regarding the PTL EOT segment-level requirements.

During the execution of this project, TTCI became aware of several industry efforts to address and improve issues with HOT and ETD. To the extent possible, TTCI engaged with various groups to see that requirements developed within the scope of this project will not conflict with other work being performed within the industry. The full set of requirements for the PTL EOT can be found in Appendix D.

3. Analysis of System Requirements, Performance Requirements, and System Architectures

The TTCI team developed a sensor architecture evaluation table (see Appendix E) to evaluate the requirements needed for the PTL EOT segment to accomplish the driving capabilities as identified. This table is based on multiple technology solutions and their ability to satisfy the desired level of performance for each capability. Each technology solution provided an indication of whether it could perform a capability, and within what level of accuracy. In addition, general information was provided including:

- An indicator of cost relative to the other solutions, ranked by a number and dollar sign (where 1$ was the cheapest solution, and 4$ the most expensive).
- A brief summary of what sensors/computing hardware the solution would include.
- An estimated cost of an individual unit at a production quantity of 10,000 units.
- Position errors for both along and across-track estimates
- Accuracy of speed measurements
- Ability to identify changes in occupied track

Two of the architectures (1$ and 2$) were also provided with corresponding architectures including Real Time Kinematic (RTK) options. The RTK versions of these options contained an additional $ in their relative cost field to distinguish them.

- The 1$ and 1$$ architectures include a low-end GNSS receiver/antenna and Inertial Measurement Unit (IMU) and provide low-cost solutions, but are unable to provide speed measurement in the case of loss of GNSS signal, or identify track changes.
- The 2$ and 2$$ architectures include a low-end GNSS receiver/antenna, more robust IMU, a basic vision sensor and a processor to support machine vision capabilities including speed measurement and identification of track occupancy change. The additional information provided by this sensor in the 2$ technology solution is processed within the PTL EOT segment, so additional data sent to the PTL HOT segment would be minimal; only indicating relative position information.
- The 3$ and 4$ options include a moderate to high-end GNSS receiver/antenna and IMU, as well as the vision sensor and processor. The 4$ also includes RTK capabilities. These architectures provide a high level of performance and include all capabilities, but at the highest cost.

A matrix was produced concurrently listing the use cases defined in Section 2 and evaluated against the capability list in Section 2.1.1 (also see Appendix B). Each use case was assigned capabilities based on what was deemed necessary to support the use case. The shared cell between each use case and a corresponding capability was populated with an estimated ranking of criticality to the use case—Low (L), Medium (M), High (H)—and the minimum architecture determined to be necessary to support the use case.

As described in Section 2.2 of this report, GNSS-only architectures (e.g., the 1$ and 1$$ architectures) were estimated to be incapable of achieving desired performance. Additionally, these architectures are not capable of performing track discrimination to an acceptable confidence, which is one of the established requirements. The 3$ and 4$ architectures exceed the level of accuracy required, but their increased cost was determined to be unjustifiable. Based on this information, the TAG reached agreement on the 2$ technology solution, as this approach meets all the desired High and Medium priorities, and all but one of the Low priorities for the PTL EOT segment at the lowest cost point.

The PTL EOT segment capabilities and performance capabilities of the 2$ architecture selected were used to validate the PTL EOT requirements developed in the prior phase. Prior phase functional requirements were evaluated for their applicability to the defined capabilities, and prior phase performance requirements were updated to reflect capabilities of the architecture selected by the TAG. This analysis highlighted requirements that were no longer valid or required modification to support the capabilities needed to satisfy the use cases. An updated set of requirements was produced from this analysis by removing requirements that were no longer applicable, modifying requirements that no longer accurately reflected defined capabilities, and adding new requirements necessary to support additional capabilities not defined in the previous phase. These requirements were traced back to capabilities to verify they were required to support the driving use cases.

4. Recommended Path Forward

The following sections outline approaches to move the PTL EOT technology forward. The first is a framework for coordinating industry efforts and developing system level requirements for the next generation of HOT and EOT/ETD functionality as a whole. The second subsection outlines a development and test phase to test the performance of the PTL EOT segment specified by the requirements developed in this phase. These approaches can occur sequentially or concurrently.

4.1 Next Generation HOT/EOT (NGHE)

TTCI and the industry have identified several areas that need to be addressed to fully leverage the safety and efficiency benefits of a HOT/EOT system. The development of a next generation HOT/EOT (NGHE) will provide capabilities beyond those currently available with HOT/EOT functionality that are expected to support safety and productivity benefits of emerging railroad technologies such as PTC, Automated Train Operation (ATO), and Quasi Moving Block (QMB) and Full Moving Block (FMB). Areas that should be addressed in the development of a NGHE are covered in the following sections.

4.1.1 NGHE Concept of Operations

A concept of operations (ConOps) document describing the capabilities and architecture of a NGHE system needs to be prepared to ensure the development of a system capable of supporting existing and future methods of railroad operation. The ConOps document should describe at a minimum:

- Improved EOT/HOT communication performance and security
- EOT point protection
- Integration with existing and emerging onboard systems
- High accuracy HOT/EOT train positioning
- Support of legacy EOT devices
- Development of use cases
- Features supporting future and emerging methods of operation

4.1.2 Requirements Development and Documentation

Systems engineering documents should be developed that encompass interoperable system, segment, and subsystem level requirements to ensure the deployment of a fully functional and interoperable NGHE system. The systems engineering documents should define:

- NGHE interoperable system functional and performance requirements
- NGHE segment and subsystem requirements
- Interfaces between NGHE segments and subsystems
- Interfaces between the NGHE system and other railroad systems with which it must integrate

4.1.3 Preliminary Hazard Analysis

Upon completion of the ConOps, a preliminary hazard analysis (PHA) should be performed to identify potential risks introduced by the NGHE. The analysis should include the identification of potential risk reduction measures.

4.2 Facilitate Development of PTL EOT and Test Performance

There is no expectation that the performance requirements developed in this project will require significant modification in the development of a NGHE system. Based on the requirements developed for the PTL EOT segment within this project, it is feasible to begin the development of a PTL EOT segment and test the performance of that segment against the performance requirements developed in this phase. Tasks that may be necessary for this project include:

- Develop a Request for Proposal (RFP) based on performance requirements
- Identify and transmit RFP to potential suppliers
- Work with TAG to select one (or more) suppliers for PTL EOT prototype development
- Work with selected supplier(s) to facilitate development of PTL EOT prototype segment
- Develop test plan for on-track testing
- On-track testing at TTC for system(s) selected
- Data analysis
- Over-the-road testing (if necessary)
- Report results

The technology developer who participated in this project on behalf of the industry has prepared a rough order of magnitude (ROM) outline for the level of effort required to develop and test a PTL EOT segment, which is included in Appendix F. This is limited to the ROM cost a vendor would incur to develop and test a PTL EOT segment and does not include the costs for systems engineering support of the development efforts or costs associated with the on-track testing efforts. This ROM does not include the associated costs for any over-the-road testing.

5. Conclusion

Many challenges remain within the railroad industry before a fully functional PTL system can be implemented. Several individual efforts are currently underway within the railroad industry to address various segment issues with existing HOT and EOT devices. This also includes efforts aimed at the future needs in the industry for train location. These individual efforts require coordination and assurance that conflicts are not created. Coordination of these individual efforts will be central to ensuring an interoperable and functional high accuracy train positioning system.

PTL EOT functionality should be viewed at a system level whereby both EOT segment and HOT segment functionality are developed concurrently to enable an overall system level capability. Specifically, while the EOT segment acts as a rear of train sensor, the PTL HOT segment remains responsible for reporting all EOT segment position and status information. This enables the HOT segment to apply its own historical information and access to a track database to EOT segment data to augment EOT segment positioning performance.

GNSS alone may not be adequate to support the capabilities that railroads have indicated will be needed for a PTL EOT segment. The requirements developed in this effort are written in such a way that does not preclude the use of additional sensor(s) to augment the capabilities of the PTL EOT segment.

6. References

1 Gage, S., Polivka, A., Ramos, A., Sloat, S., Positive Train Location: Final Report, Technical Report, Report No. DOT/FRA/ORD-18/17. Washington, DC: U.S. Department of Transportation, Federal Railroad Administration, September 2017.

2 The Rail Safety Improvement Act of 2008, Public Law 110–432, 122 STAT. 4848, October 2008.

Appendix A.
Use Case Summary

1 Capability/Use Case Matrix Overview and Notes

The Positive Train Location (PTL) End-of-Train (EOT) Capability/Use Case Matrix provides a method of identifying which EOT-related PTL capabilities are required in each of various use cases associated with railroad operations, incidents, and system failures. Each cell contains a priority assignment (L – Low, M – Medium, H – High) to indicate a preliminary qualitative assessment of how important that capability is to the railroads in each use case. Each cell also contains a cost representation (a $ value) for the minimum EOT configuration required to sufficiently perform that capability in that use case. The four candidate EOT configurations are defined in a separate document. Empty cells are assigned no priority for that capability in the context of the associated use case.

2 Capability Definitions

- **C-01a - Determine Relative Position of EOT Along Track and Proximity to POI:** Determine the position of the EOT along track based on railroad frames of reference when Global Navigation Satellite System (GNSS) signals are available. Determine position of EOT relatively to points of interest (POI) such as clearance points of signals, switches, crossings, and other infrastructure. It is assumed that the EOT will *not* have access to a track database, so the determination of relative distance between the EOT and a POI will be done at the head of the train (either in the PTC segment or the PTL HOT segment), where track data is available. The EOT's will only contribute its location information to this relative distance determination process.
- **C-01b - Determine Relative Position of EOT Along Track and Proximity to POI after GNSS loss:** Determine the position of the EOT along track based on railroad frames of reference without GNSS position data. Determine the position of EOT relatively to POI such as clearance points of signals, switches, crossings, and other infrastructure without GNSS position data.
- **C-02a - EOT Track Discrimination:** Identify which track the EOT occupies when near to other (e.g., parallel) tracks when GNSS signals are available.
- **C-02b - EOT Track Discrimination After GNSS Loss:** Identify which track the EOT occupies when near to other tracks without GNSS position data.
- **C-03a - Determine EOT Speed:** Determine the speed at which the EOT is moving when GNSS signals are available.
- **C-03b - Determine EOT Speed After GNSS Loss:** Determine the speed at which the EOT is moving without GNSS position data.
- **C-04a - Estimate EOT Position After Reinitialization While in Motion:** In the case of a reinitialization of the EOT while in motion, where the EOT position history is unknown, the PTL system determines EOT position. GNSS is required.
- **C-04b - Reinitialization While in Motion w/out GNSS for Conventional ETD Functions:** In the case of a reinitialization of the EOT while the train is in motion, where the EOT position history is unknown and GNSS is not available, the EOT retains basic ETD functionality.
- **C-05 - Estimate EOT Position Uncertainty and Confidence:** The PTL system estimates the uncertainty and level of confidence associated with position estimates, whether or not GNSS signals are available.
- **C-06 - Determine Train Integrity (EOT BPP, Train Length, Speed Delta):** The PTL system identifies when unintentional train separation has occurred.
- **C-07 - Perform Closed Loop Emergency BPP Reduction at EOT:** The EOT initiates an emergency BPP reduction via the ETD, using a closed-loop communications protocol with the head of train (HOT) device.

- **C-08 - Determine EOT Segment Health:** The PTL system determines health of the EOT segment.
- **C-09 - Facilitate Diagnosis/Diagnose EOT Component Failures:** The PTL system identifies component failures when they occur and provides an interface that facilitates the diagnosis of failures for railroad employees.
- **C-10 - Facilitate Replacement/Replace Failed EOT Components:** The PTL system facilitates replacement of failed components through both physical design (removal/connection of modular components) and software (interfacing with newly installed components).
- **C-11 - Graceful Degradation in the Event of PTL Component Failure:** The EOT gracefully returns to a minimum state of standard ETD functionality (or better) in the event of component failure.
- **C-12 - Pair/Unpairing EOT w/HOT:** The EOT pairs with the correct HOT device.
- **C-13 - Interface w/EOT Radio, ETD, and Loco Comms Manager:** The HOT portion of the PTL system interfaces with the comms manager device on board the locomotive used to manage communication among the onboard radios and onboard applications (including PTC). The locomotive crew interface with the PTL system is assumed to be via the onboard PTC user interface. The PTL EOT segment interfaces with the radios (railroad band and cellular) at the EOT and with the conventional End-of-Train device (ETD) equipment, providing the necessary queuing and multiplexing to allow the PTL EOT and the ETD to both share the same radio(s).
- **C-14 - Interface w/Operator:** The EOT provides an interface for operators and maintainers to perform basic configuration, self-test, and pairing functions at the ETD.
- **C-15 – Report General Location – Global Coordinates:** The EOT reports its global coordinates, independent of railroad reference frames.

3. Operational Scenario – (OS-01) Forward Movement (HOT is lead-end of the train)

3.1 Operation Routine Cases

3.1.1 Use Case – (UC-1.1) Non-Turnout Movement

Name	**Non-Turnout Movement**
Description	*Movement through territory other than switching and entering/leaving sidings, spurs, junctions, cross-overs, or yards/terminals. Train is not part of a close-following move.*
Variations	• Tangent • Curve • Proximity to POI (clearing or approaching relevant track features, infrastructure, authority limit)
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals* • **(C-01b) - Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals during GNSS loss* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position in the case of reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length,**

Name	Non-Turnout Movement
	Speed Delta) *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	Tangent or curve may change requirements for position update rate

3.1.2 Use Case – (UC-1.2) Facing Point Turnout Operations

Name	Facing Point Turnout Operations
Description	*Railroad operations such as entering sidings, spurs, junctions, cross-overs, yards/terminals, or switching*
Variations	• Yards/terminals • Sidings • Cross-overs • Junctions • Spurs • Separating (intentional) • Coupling
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches, and clearance points* • **(C-01b) - Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches,*

Name	Facing Point Turnout Operations
	and clearance points during GNSS loss • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position during in the case of unexpected reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/ EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	Increased along track resolution may be required for clearance points

3.1.3 Use Case – (UC-1.3) Trailing Point Turnout Operations

Name	Trailing Point Turnout Operations
Description	*Railroad operations such as leaving sidings, spurs, junctions, cross-overs, yards/terminals, or switching*

Name	Trailing Point Turnout Operations
Variations	• Yards/terminals • Sidings • Cross-overs • Junctions • Spurs • Separating (intentional) • Coupling
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches, and clearance points* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches, and clearance points without GNSS data* • **(C-04a) Estimate EOT Position w/out Position History** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position during in the case of unexpected reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component**

Name	Trailing Point Turnout Operations
	Failure *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/ EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	Increased along track resolution may be required for clearance points

3.1.4 Use Case - (UC-1.4) Close-Following Moves (CFM)

Name	**Close Following Moves (CFM)**
Description	*Train movements where the PTL train is being closely followed by another train. Excluding yard and siding operations.*
Variations	• Constant Speed • Accelerating • Braking • Grade
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track without GNSS data* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position in the case of reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be*

Name	**Close Following Moves (CFM)**
	added to EOT position estimates • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data.* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure.* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT.* • **(C-15) Report General Location** *Allocation: EOT* *Required for: ETD Geolocation*
Notes	May require increased EOT reporting rate

3.2 Operation Exception Cases

3.2.1 Use Case – (UC-1.5) Unintentional Train Separation

Name	**Unintentional Train Separation**
Description	*Separation of the train not initiated by the train crew for railroad operations*
Variations	None

Name	Unintentional Train Separation
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the along track position of the section of the train containing the EOT device* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the along track position of the section of the train containing the EOT device without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides without GNSS data* • **(C-03a) Determine EOT Speed** *Allocation: PTL System (EOT+HOT)* *Required for: Providing a speed estimate for the section of the train containing the EOT* • **(C-03b) Determine EOT Speed After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing a speed estimate for the section of the train containing the EOT without GNSS data.* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position during in the case of unexpected reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)**

<table>
<tr><th>Name</th><th>Unintentional Train Separation</th></tr>
<tr><td></td><td>
Allocation: PTL System (EOT+HOT)
Required for: Identifying brake status of the section of the train containing the EOT

(C-07) Perform Closed Loop Emergency BPP Reduction at EOT
Allocation: EOT
Required for: Stopping the section of the train containing the EOT
(C-08) Determine EOT Segment Health
Allocation: EOT
Required for: Identifying component failure in the EOT for validation of position data
(C-11) Graceful Degradation in the Event of PTL Component Failure
Allocation: PTL System (EOT+HOT)
Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure
(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager
Allocation: PTL System (EOT+HOT)
Required for: Communication between EOT and HOT
(C-15) Report General Location
Allocation: EOT
Required for: ETD Geolocation

Allocation: EOT
Required for: Identifying component failure in the EOT for validation of position data

(C-11) Graceful Degradation in the Event of PTL Component Failure
Allocation: PTL System (EOT+HOT)
Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure
(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager
Allocation: PTL System (EOT+HOT)
Required for: Communication between EOT and HOT
(C-15) Report General Location
Allocation: EOT
Required for: ETD Geolocation

</td></tr>
<tr><td>Notes</td><td></td></tr>
</table>

3.2.2 Use Case - (UC-1.6) Crew Initiated Emergency Brake Application

Name	**Crew Initiated Emergency Brake Application**
Description	*Emergency brake application initiated by the train crew or PTC*
Variations	None
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position in the case of reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-07) Perform Closed Loop Emergency BPP Reduction at EOT** *Allocation: EOT* *Required for: Performing an emergency brake at the EOT in conjunction with the HOT* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	

3.3 PTL System Exception Cases

3.3.1 Use Case – (UC-1.7) EOT Reinitialization While in Motion

Name	**EOT Reinitialization While in Motion**
Description	*The EOT segment reinitializes during train movement.*
Variations	• EOT/HOT position history known • EOT/HOT position history unknown
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track.* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides without GNSS data* • **(C-03a) Determine EOT Speed** *Allocation: PTL System (EOT+HOT) Required for: EOT initialization* • **(C-03b) Determine EOT Speed After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: EOT initialization without GNSS* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Verify train integrity* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation*

Name	EOT Reinitialization While in Motion
	of position data • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure.* • **(C-12) Pairing/Unpairing EOT w/HOT** *Allocation: PTL System (EOT+HOT)* *Required for: Re-establishing a communication link between the EOT and HOT after either or both segments reboot* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT* • **(C-15) Report General Location** *Allocation: EOT* *Required for: ETD Geolocation*
Notes	

3.3.2 Use Case – (UC-1.8) EOT Component Failure

Name	EOT Component Failure
Description	*A component of the EOT device ceases to operate correctly.*
Variations	None
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-09) Facilitate Diagnosis/Diagnose EOT Component Failure** *Allocation: EOT* *Required for: Ensuring component failures in the EOT device can easily be identified and troubleshot* • **(C-10) Facilitate Replacement/Replace Failed EOT Components** *Allocation: EOT* *Required for: Ensuring failed components in the EOT device can be easily replaced, without requiring replacement of the entire device* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT.* • **(C-14) Interface w/Operator**

Name	EOT Component Failure
	Allocation: EOT *Required for: Providing a basic interface to configure the EOT when not connected to a PTL system*
Notes	

3.3.3 Use Case – (UC-1.9) EOT Communication Coverage Loss or Interference

Name	EOT Communication Coverage Loss or Interference
Description	*The EOT device loses communication with the HOT, or experiences degraded communication quality. This would be due to noise, interference, RF path blockage, etc., but not due to radio equipment failure because that is addressed in the use case immediately above.*
Variations	None
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT to help identify source of communication issues* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	

4. Operational Scenario – (OS-02) Reverse Movement *(EOT is lead-end of train)*

4.1 Operation Routine Cases

4.1.1 Use Case – (UC-2.1) Non-Turnout Movement

Name	**Non-Turnout Movement**
Description	*Movement through territory other than switching and entering/leaving sidings, spurs, junctions, cross-overs, or yards/terminals. Train is not part of a close-following move.*
Variations	• Tangent • Curve • Proximity to POI (clearing, track features, infrastructure, authority limit)
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals* • **(C-01b) - Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals during GNSS loss* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position in the case of reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length,**

Name	Non-Turnout Movement
	Speed Delta) *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	Tangent or curve may change requirements for position update rate

4.1.2 Use Case – (UC-2.2) Facing Point Turnout Operations

Name	Facing Point Turnout Operations
Description	*Railroad operations such as entering sidings, spurs, junctions, cross-overs, yards/terminals, or switching*
Variations	• Yard N/X • Sidings • Cross-overs • Junctions • Spurs • Entering/leaving siding • Separating • Coupling

Name	**Facing Point Turnout Operations**
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches, and clearance points* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches, and clearance points without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides without GNSS data* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position during in the case of unexpected reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined.* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data*

Name	Facing Point Turnout Operations
	• **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	Increased along track resolution may be required for clearance points.

4.1.3 Use Case – (UC-2.3) Trailing Point Turnout Operations

Name	Trailing Point Turnout Operations
Description	*Railroad operations such as leaving sidings, passing junctions, cross-overs, or switching*
Variations	• Yard N/X • Sidings • Cross-overs • Junctions • Spurs • Entering/leaving siding • Separating • Coupling
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches, and clearance points* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and determining distance to infrastructure such as signals, switches, and clearance points without GNSS data* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position during in the case*

Name	Trailing Point Turnout Operations
	of unexpected reinitialization of the EOT or the entire PTL system • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	Increased along track resolution may be required for clearance points.

4.2 Operation Exception Cases

4.2.1 Use Case – (UC-2.4) Unintentional Train Separation

Name	Unintentional Train Separation
Description	*Separation of the train not initiated by the train crew for railroad operations.*
Variations	None

Name	Unintentional Train Separation
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the along track position of the section of the train containing the EOT device* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the along track position of the section of the train containing the EOT device without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides without GNSS data* • **(C-03a) Determine EOT Speed** *Allocation: PTL System (EOT+HOT)* *Required for: Providing a speed estimate for the section of the train containing the EOT* • **(C-03b) Determine EOT Speed After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing a speed estimate for the section of the train containing the EOT without GNSS* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position during in the case of unexpected reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)**

Name	**Unintentional Train Separation**
	Allocation: PTL System (EOT+HOT) *Required for: Identifying brake status of the section of the train containing the EOT* • **(C-07) Perform Closed Loop Emergency BPP Reduction at EOT** *Allocation: EOT* *Required for: Stopping the section of the train containing the EOT* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT* • **(C-15) Report General Location** *Allocation: EOT* *Required for: ETD Geolocation*
Notes	

4.2.2 Use Case - (UC-2.5) Crew Initiated Emergency Brake Application

Name	**Crew Initiated Emergency Brake Application**
Description	*Emergency brake application initiated by the train crew or PTC.*
Variations	None

Name	Crew Initiated Emergency Brake Application
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position in the case of reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-07) Perform Closed Loop Emergency BPP Reduction at EOT** *Allocation: EOT* *Required for: Performing an emergency brake at the EOT in conjunction with the HOT* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	

4.3 PTL System Exception Cases

4.3.1 Use Case – (UC-2.6) EOT Reinitialization While in Motion

Name	**EOT Reinitialization While in Motion**
Description	*The EOT segment reinitializes during train movement.*
Variations	None

Name	EOT Reinitialization While in Motion
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the section of the train containing the EOT device resides without GNSS data* • **(C-03a) Determine EOT Speed** *Allocation: PTL System (EOT+HOT) Required for: EOT initialization* • **(C-03b) Determine EOT Speed After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: EOT initialization without GNSS* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Verify train integrity* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-12) Pairing/Unpairing EOT w/HOT** *Allocation: PTL System (EOT+HOT)*

Name	EOT Reinitialization While in Motion
	Required for: Re-establishing a communication link between the EOT and HOT after either or both segments reboot • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT* • **(C-15) Report General Location -** *Allocation: EOT* *Required for: ETD Geolocation*
Notes	

4.3.2 Use Case – (UC-2.7) EOT Component Failure

Name	EOT Component Failure
Description	*A component of the EOT device ceases to operate correctly.*
Variations	None
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-09) Facilitate Diagnosis/Diagnose EOT Component Failure** *Allocation: EOT* *Required for: Ensuring component failures in the EOT device can easily be identified and troubleshot* • **(C-10) Facilitate Replacement/Replace Failed EOT Components** *Allocation: EOT* *Required for: Ensuring failed components in the EOT device can be easily replaced, without requiring replacement of the entire device* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	

4.3.3 Use Case – (UC-2.8) EOT Communication Coverage Loss or Interference

Name	**EOT Communication Coverage Loss or Interference**
Description	*The EOT device loses communication with the HOT, or experiences degraded communication quality.*
Variations	None
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT to help identify source of communication issues* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	

5. Operational Scenario – (OS-03) Stationary

5.1 Operation Routine Cases

5.1.1 Use Case – (UC-3.1) PTC System Initialization/Termination

Name	**PTC System Initialization/Termination**
Description	*The PTC system initializes, aided by information from the PTL system.*
Variations	None
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides without GNSS data* • **(C-03a) Determine EOT Speed** *Allocation: PTL System (EOT+HOT) Required for: EOT initialization* • **(C-03b) Determine EOT Speed After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: EOT initialization without GNSS* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT*

Name	PTC System Initialization/Termination
	Required for: Identifying component failure in the EOT for validation of position data • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT* • **(C-14) Interface w/Operator** *Allocation: EOT* *Required for: Providing a basic interface to configure the EOT when not connected to a PTL system.*
Notes	

5.1.2 Use Case – (UC-3.2) EOT Initialization/Termination

Name	EOT/PTL System Initialization/Termination
Description	
Variations	None
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides without GNSS data. This capability is not feasible in this use case.* • **(C-03a) Determine EOT Speed** *Allocation: PTL System (EOT+HOT)* *Required for: Verifying EOT speed is 0 prior to PTC initialization*

Name	EOT/PTL System Initialization/Termination
	• **(C-03b) Determine EOT Speed After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Verifying EOT speed is 0 prior to PTC initialization without GNSS data* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-12) Pairing/Unpairing EOT w/HOT** *Allocation: PTL System (EOT+HOT)* *Required for: Establishing a communication link between the EOT and HOT* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT* • **(C-14) Interface w/Operator** *Allocation: PTL System (EOT)* *Required for: Supporting* • **(C-15) Report General Location** *Allocation: EOT* *Required for: ETD Geolocation*
Notes	

5.1.3 Use Case – (UC-3.3) Train is Idle

Name	**Train is Idle**
Description	*Train is stopped and waiting (such as at a signal, or in a siding)*
Variations	None

Name	**Train is Idle**
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and relative to signals and other track infrastructure* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position along the track and relative to signals and other track infrastructure without GNSS data without GNSS data* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)** *Allocation: PTL System (EOT+HOT) Required for: Identifying pull-aparts* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	

5.2 Operation Exception Cases

5.2.1 Use Case – (UC-3.4) Unintentional Train Separation

Name	**Unintentional Train Separation**
Description	*Separation of the train not initiated by the train crew for railroad operations*
Variations	None

Name	Unintentional Train Separation
Associated Capabilities *Allocation Explanation of Inclusion*	• **(C-01a) Determine Relative Position of EOT Along Track and Proximity to POI** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the along track position of the section of the train containing the EOT device* • **(C-01b) Determine Relative Position of EOT Along Track and Proximity to POI After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the along track position of the section of the train containing the EOT device without GNSS data* • **(C-02a) EOT Track Discrimination** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides* • **(C-02b) EOT Track Discrimination After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimate of the track where the EOT resides without GNSS data* • **(C-03a) Determine EOT Speed** *Allocation: PTL System (EOT+HOT)* *Required for: Providing a speed estimate for the section of the train containing the EOT* • **(C-03b) Determine EOT Speed After GNSS Loss** *Allocation: PTL System (EOT+HOT)* *Required for: Providing a speed estimate for the section of the train containing the EOT without GNSS data* • **(C-04a) Estimate EOT Position After Reinitialization While in Motion** *Allocation: PTL System (EOT+HOT)* *Required for: Providing an estimated EOT position during in the case of unexpected reinitialization of the EOT or the entire PTL system* • **(C-04b) Reinitialization While in Motion w/out GNSS for Conventional ETD Functions** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring basic ETD functionality is not lost in the case of EOT reinitialization when position cannot be determined* • **(C-05) Estimate EOT Position Uncertainty and Confidence** *Allocation: PTL System (EOT+HOT)* *Required for: Determining amount of safety margin that must be added to EOT position estimates* • **(C-06) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)**

Name	Unintentional Train Separation
	Allocation: PTL System (EOT+HOT) *Required for: Identifying brake status of the section of the train containing the EOT* • **(C-07) Perform Closed Loop Emergency BPP Reduction at EOT** *Allocation: EOT* *Required for: Stopping the section of the train containing the EOT* • **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-11) Graceful Degradation in the Event of PTL Component Failure** *Allocation: PTL System (EOT+HOT)* *Required for: Ensuring ETD continues to perform base functions in the case of EOT component failure* • **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT* • **(C-15) Report General Location** *Allocation: EOT* *Required for: ETD Geolocation*
Notes	

5.3 PTL System Exception Cases

5.3.1 Use Case – (UC-3.5) EOT Component Failure

Name	**EOT Component Failure**
Description	*A component of the EOT device ceases to operate correctly.*
Variations	None

Name	EOT Component Failure
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-08) Determine EOT Segment Health** *Allocation: EOT* *Required for: Identifying component failure in the EOT for validation of position data* • **(C-09) Facilitate Diagnosis/Diagnose EOT Component Failure** *Allocation: EOT* *Required for: Ensuring component failures in the EOT device can easily be identified and troubleshot* • **(C-10) Facilitate Replacement/Replace Failed EOT Components** *Allocation: EOT* *Required for: Ensuring failed components in the EOT device can be easily replaced, without requiring replacement of the entire device* • **(C-11) Graceful Degradation in the Event of PTL Component Failure**
Notes	

5.3.2 Use Case – (UC-3.6) EOT Communication Coverage Loss or Interference

Name	EOT Communication Coverage Loss or Interference
Description	*The EOT device loses communication with the HOT, or experiences degraded communication quality.*
Variations	None
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-13) Interface w/EOT Radio, ETD, and Loco Comms Manager** *Allocation: PTL System (EOT+HOT)* *Required for: Communication between EOT and HOT*
Notes	

6. Operational Scenario – (OS-05) Off Track

6.1 Use Case – (UC-4.1) Inventory Monitoring

Name	**Inventory Monitoring**
Description	*Tracking location of an EOT device when not connected to a train and/or paired to an HOT. The device might not be near a track, so absolute coordinates must be reported.*
Variations	None
Associated Capabilities *Allocation* *Explanation of Inclusion*	• **(C-14) Interface w/Operator** *Allocation: EOT* *Required for: Providing a basic interface to configure the EOT when not connected to a PTL system* • **(C-15) Report General Location – Global Coordinates** *Allocation: EOT* *Required for: Reporting EOT position when not connected to a PTL system*
Notes	

Notes:

UC-1.5, UC-1.7, UC-2.4, UC-2.6

- Use cases assume that track is known at the time of separation (or reinitialization).

UC-1.1 (C-01a, C01b), UC-1.2 (C01a, C01b), UC-1.3 (C01a, C01b), UC-2.1 (C-01a, C01b), UC- 2.2 (C01a, C01b), UC-2.3 (C01a, C01b)

- The 2$'s in these 6 cells could change to 1$ if 50' of margin (at 8 9's of confidence) is acceptable.

Appendix B.
Use Case - Capability Matrix

Forward Movement OS-01	Use Case	C-01a Determine Relative Position of EOT Along Track and Proximity to T (Allocation: PTL System)	C-01b Determine Rel. Pos'n of EOT Along Trk & Prxmty to POI after GNSS (Allocation: PTL System)	C-02a EOT Track (Allocation: PTL System)	C-02b EOT Track Discrimination after (Allocation: PTL System)	C-03a Determine (Allocation: PTL System)	C-03b Determine EOT Speed after (Allocation: PTL System)	C-04a Estimate EOT Position After Reinit while in Motion (GNSS (Allocation: PTL System)	C-04b Reinit while in Motion w/out GNSS for Conventional ETD (Allocation: PTL System)	C-05 Estimate EOT Position Uncertainty and (Allocation: PTL System)	C-06 Determine Train Integrity (EOT BPP, Train Length, Speed (Allocation: PTL System)	C-07 Perform Closed-Loop Emergency BPP Reduction (Alloca tion:)	C-08 Determine EOT Segment (Alloca tion:)	C-09 Facilitate Diagnosis/Diagnose EOT Component (Allocation: EOT,)	C-10 Facilitate Replacement/Replace Failed EOT (Allocation: EOT,)	C-11 Graceful Degradation in the Event of PTL Component (Allocation: PTL System)	C-12 Pair/Unpairing (Allocation: PTL System)	C-13 Interface w/EOT Radio, ETD, and Loco Comms (Allocation: PTL System)	C-14 Interface (Alloca tion:)	C-15 Report General Location - Global (Alloca tion:E O)
Operation Routine Cases																				
Non-Turnout Movement *tangent, curve, proximity to POI (Clearing, Track Features, Infrastructure, Authority Limit)*	UC-1.1	H 2$	H 2$					H 1$	H 1$	H 1$	H 1$		H 1$			H 1$		H 1$		
Facing Point Turnout Operations *yard N/X, sidings, x-overs, jcts, spurs, entering/leaving siding, separating, coupling*	UC-1.2	H 2$	H 2$					H 2$	H 1$	H 1$	H 1$		H 1$			H 1$		H 1$		
Trailing Point Turnout Operations *yard N/X, sidings, x-overs, jcts, spurs, entering/leaving siding, separating, coupling*	UC-1.3	H 2$	H 2$					H 2$	H 1$	H 1$	H 1$		H 1$			H 1$		H 1$		
Close-Following Moves *constant speed, accelerating, braking, grade*	*UC-1.4*	H 1$	H 2$					H 2$	H 1$	H 1$	H 1$		H 1$			H 1$		H 1$		H 1$
Operation Exception Cases																				
Unintentional Train Separation	UC-1.5	H 2$	H 2$	L 2$	L 2$	H 1$	H 2$	H 2$	H 1$	H 1$	H 1$	H 1$	H 1$			H 1$		H 1$		H 1$
Crew Initiated Emergency Brake Application	UC-1.6							M 1$	M 1$	M 1$	H 1$	H 1$	H 1$			H 1$		H 1$		
PTL System Exception Cases																				
EOT Reinitialization While in Motion	UC-1.7	L 1$	L 2$	L 2$	L 2$	M 1$	M 2$			L 1$	H 1$		H 1$			H 1$	H 1$	H 1$		H 1$
EOT Component Failure	UC-1.8												H 1$	H 1$	M 1$	H 1$		H 1$	H 1$	
EOT Communication Coverage Loss or Interference	UC-1.9												M 1$					H 1$		

Use Cases																					
Reverse Movement OS-02	**Operation Routine Cases**																				
	Non-Turnout Movement *tangent, curve, proximity to POI (Clearing, Track Features, Infrastructure, Authority Limit)*	UC-2.1	H 2$	H 2$					H 1$	H 1$	H 1$	H 1$		H 1$			H 1$		H 1$		
	Facing Point Turnout Operations *yard N/X, sidings, x-overs, jcts, spurs, entering/leaving siding, separating, coupling*	UC-2.2	H 2$	H 2$	H 2$	H 2$			H 2$	H 1$	H 1$	H 1$		H 1$			H 1$		H 1$		
	Trailing Point Turnout Operations *yard N/X, sidings, x-overs, jcts, spurs, entering/leaving siding, separating, coupling*	UC-2.3	H 2$	H 2$					H 2$	H 1$	H 1$	H 1$		H 1$			H 1$		H 1$		
	Operation Exception Cases																				
	Unintentional Train Separation	UC-2.4	H 1$	M 2$	L 2$	L 2$	H 1$	H 2$	M 2$	M 1$	H 1$	H 1$	H 1$	H 1$			H 1$		H 1$		H 1$
	Crew Initiated Emergency Brake Application	UC-2.5							M 2$	M 1$		H 1$	H 1$	H 1$			H 1$		H 1$		
	PTL System Exception Cases																				
	EOT Reinitialization While in Motion	UC-2.6	L 1$	L 2$	L 2$	L 2$	M 1$	M 2$			L 1$	H 1$		H 1$			H 1$	H 1$	H 1$		H 1$
	EOT Component Failure	UC-2.7												H 1$	H 1$	M 1$	H 1$		H 1$	H 1$	
	EOT Communication Coverage Loss or Interference	UC-2.8												M 1$					H 1$		
Stationary OS-03	**Operation Routine Cases**																				
	PTC System Initialization/Termination	UC-3.1	M 1$	M 2$	L 2$	L 2$	H 1$	H 1$			M 1$	H 1$		H 1$			H 1$		H 1$	H 1$	
	EOT Initialization/Termination	UC-3.2	M 1$	M 2$	L 4$	H NF	H 1$	H 2$			H 1$	H 1$		H 1$			H 1$	H 1$	H 1$	H 1$	H 1$
	Train Is Idle	UC-3.3	L 1$	L 2$							L 1$	H 1$		H 1$			H 1$		H 1$		
	Operation Exception Cases																				
	Unintentional Train Separation	UC-3.4	H 1$	M 2$	L 2$	L 2$	H 1$	H 2$	M 2$	M 1$	H 1$	H 1$	H 1$	H 1$			H 1$		H 1$		H 1$
	PTL System Exception Cases																				
	EOT Component Failure	UC-3.5												H 1$	H 1$	M 1$	H 1$		H 1$	H 1$	
	EOT Communication Coverage Loss or Interference	UC-3.6																	H 1$		
Off Track OS-05	Inventory Monitoring	UC-4.1																		H 1$	H 1$

Key

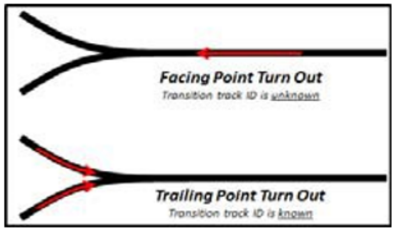
LMH NF	Not Feasible
LMH 1$	1$ Capability Only
LMH 2$	1$–2$ Capabilities Only
LMH 3$	1$–3$ Capabilities Only
LMH 4$	All Capabilities

	Capabilities	Capability Notes
	Determine Relative Position of EOT Along Track and Proximity to POI	HOT refines EOT position
C-01a	Allocation: PTL System (EOT+HOT)	
	Determine Rel. Pos'n of EOT Along Trk & Prxmty to POI after GNSS loss	
C-01b	Allocation: PTL System (EOT+HOT)	
	EOT Track Discrimination	
C-02a	Allocation: PTL System (EOT+HOT)	
	EOT Track Discrimination after GNSS loss	
C-02b	Allocation: PTL System (EOT+HOT)	Dead Reckoning is an HOT capability
	Determine EOT Speed	
C-03a	Allocation: PTL System (EOT+HOT)	
	Determine EOT Speed after GNSS loss	
C-03b	Allocation: PTL System (EOT+HOT)	In case of Dead Reckoning, HOT estimates EOT position confidence
	Estimate EOT Position After Reinit. while in Motion (GNSS Reqd)	
C-04a	Allocation: PTL System (EOT+HOT)	
	Reinit while in Motion w/out GNSS for Conventional ETD Functions	
C-04b	Allocation: PTL System (EOT+HOT)	
	Estimate EOT Position Uncertainty and Confidence	Required in all operating scenarios

	Capabilities	Capability Notes
C-05	Allocation: PTL System (EOT+HOT) Determine Train Integrity (EOT BPP, Train Length, Speed Delta)	
C-06	Allocation: PTL System (EOT+HOT) Perform Closed-Loop Emergency BPP Reduction at EOT	
C-07	Allocation: EOT Determine EOT Segment Health	
C-08	Allocation: EOT Facilitate Diagnosis/Diagnose EOT Component Failures	
C-09	Allocation: EOT, EOT+Worker Facilitate Replacement/Replace Failed EOT Components	HOT compares EOT position to track database
C-10	Allocation: EOT, EOT+Worker Graceful Degradation in the Event of PTL Component Failure	
C-11	Allocation: PTL System (EOT+HOT) Pair/Unpairing EOT w/HOT	
C-12	Allocation: PTL System (EOT+HOT) Interface w/EOT Radio, ETD, and Loco Comms Manager	
C-13	Allocation: PTL System (EOT+HOT) Interface w/Operator at ETD	

	Capabilities	Capability Notes
C-14	Allocation: EOT Report General Location - Global Coordinates	
C-15	Allocation: EOT	
C-05	Estimate EOT Position Confidences Allocation: PTL System (EOT+HOT)	

Sensor Architecture Use Distribution



Number of Cases = 202

ALL REQUIREMENTS

Sensor Architecture Use Distribution

1$	8	0	0	0	7	1	3	12	16	17	5	22	3	3	20	3	23	6	74.1%	55.2%
2$	7	15	7	7	0	6	9	0	0	0	0	0	0	0	0	0	0	0	25.4%	44.0%
3$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0.0%
4$	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.5%	0.9%
																			100.0%	100.0%

High Priority UC Fulfillment

1$	3	0	0	0	5	1	2	8	11	17	5	20	3	0	20	3	23	6	81.9%	62.7%
2$	7	8	1	1	0	4	6	0	0	0	0	0	0	0	0	0	0	0	17.4%	36.0%
3$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0.0%
4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0.0%
																			99.4%	98.7%

Medium Priority UC Fulfillment

1$	2	0	0	0	2	0	1	4	2	0	0	2	0	3	0	0	0	0	64.0%	55.0%
2$	0	4	0	0	0	2	3	0	0	0	0	0	0	0	0	0	0	0	36.0%	45.0%
3$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0.0%
4$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0.0%
																			100.0%	100.0%

Low Priority UC Fulfillment

1$	3	0	0	0	0	0	0	0	3	0	0	0	0	0	0	0	0	0	27.3%	27.3%
2$	0	3	6	6	0	0	0	0	0	0	0	0	0	0	0	0	0	0	68.2%	68.2%
3$	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0.0%	0.0%
4$	0	0	1	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	4.5%	4.5%
																			100%	100%

All Capabilities

Forward Motion			Reverse Motion			Stationary		Total
H	83%	81	H	78%	72	H	69%	55
M	9%		M	13%		M	16%	
L	9%		L	10%		L	15%	
1$	75%		1$	72%		1$	76%	
2$	25%		2$	28%		2$	20%	
3$	0%		3$	0%		3$	0%	
4$	0%		4$	0%		4$	2%	

Performance Capabilities (C-01 to C-05)

Forward Motion		Total	Reverse Motion		Total	Stationary		Total
H	84%	32	H	60%	35	H	38%	26
M	9%		M	20%		M	31%	
L	6%		L	20%		L	31%	
1$	50%	32	1$	43%	35	1$	50%	26
2$	50%		2$	57%		2$	42%	
3$	0%	32	3$	0%	35	3$	0%	26
4$	0%		4$	0%		4$	4%	

PERFORMANCE REQUIREMENTS

	H	M	L
1$	62.7%	55.0%	27.3%
2$	36.0%	45.0%	68.2%
3$	0.0%	0.0%	0.0%
4$	0.0%	0.0%	4.5%

PERFORMANCE REQUIREMENTS

	H	M	L
1$	47	11	6
2$	27	9	15
3$	0	0	0
4$	0	0	1

115

All REQUIREMENTS

	H	M	L
1$	127	16	6
2$	27	9	15
3$	0	0	0
4$	0	0	1

201

PERFORMANCE REQUIREMENTS

	H	M	L
1$	0	0	0
2$	0	1	0
3$	0	0	2
4$	0	0	1

Satellite Visibility at End of Train

Author: Shön Sloat

June 28, 2019

Transportation Technology Center, Inc.

1. Analysis Approach and Assumptions

- Analysis compares HOT full hemisphere with EOT 1/2 hemisphere satellite view
- Since Satellite-based Augmentation System (SBAS) satellites are not directly used in GNSS position solution (beyond ionospheric correction), SBAS satellite number will not be included.
- Presently, only GPS and Galileo satellite constellations are allowed for GNSS receiver usage by U.S. railroads.
- Along with # of observable satellites, GDOP* provides additional critical information re GNSS receiver performance.
- For brevity, a single site location is both analytically and empirically characterized.

Figure C1. GDOP (geometric dilution of precision) describes degradation in position accuracy due to the relative position of the GPS satellites

GPS + Galileo Satellites Within a 24-hour 180-degree View
Full Hemisphere View – atop Locomotive at Front of Train

Coordinates: [30.0719 N, 94.1558 W]

- Only a few instances of a minimal number of 12 satellites is observed while most instances are >> 12
- GDOP is further uniformly Good at the HOT with full hemisphere available.

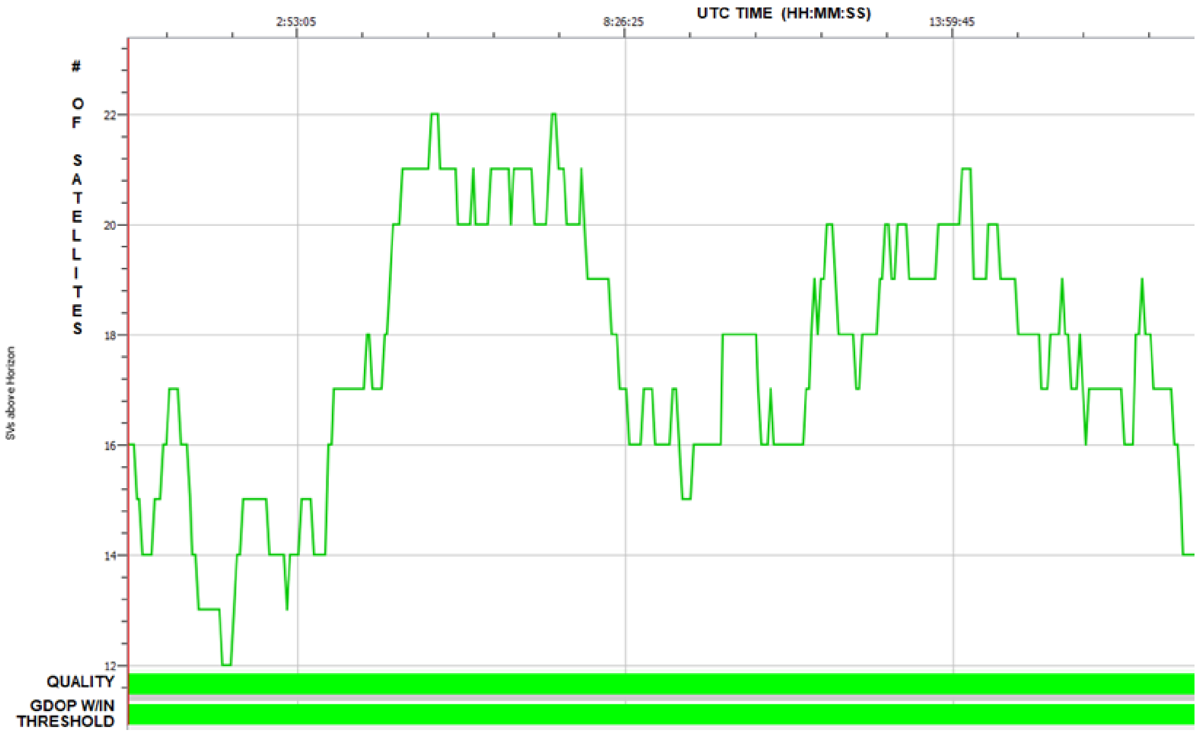


Figure C2. # GPS + Galileo satellites within a 24-hour 180-degree view

GPS + Galileo Satellites Within a 24-hour 9-degree View
1/2 Hemisphere View – at EOT

Coordinates: [30.0719 N, 94.1558 W]

- For the same position and 24-hour time interval, satellite observability drops to 1/4, rather than 1/2 as anticipated.
- Consequently, satellite visibility as low as three is observed which results in no or marginal positioning capability.
- Moreover, GDOP now varies from OK to very poor which further significantly degrades GPS positioning performance.

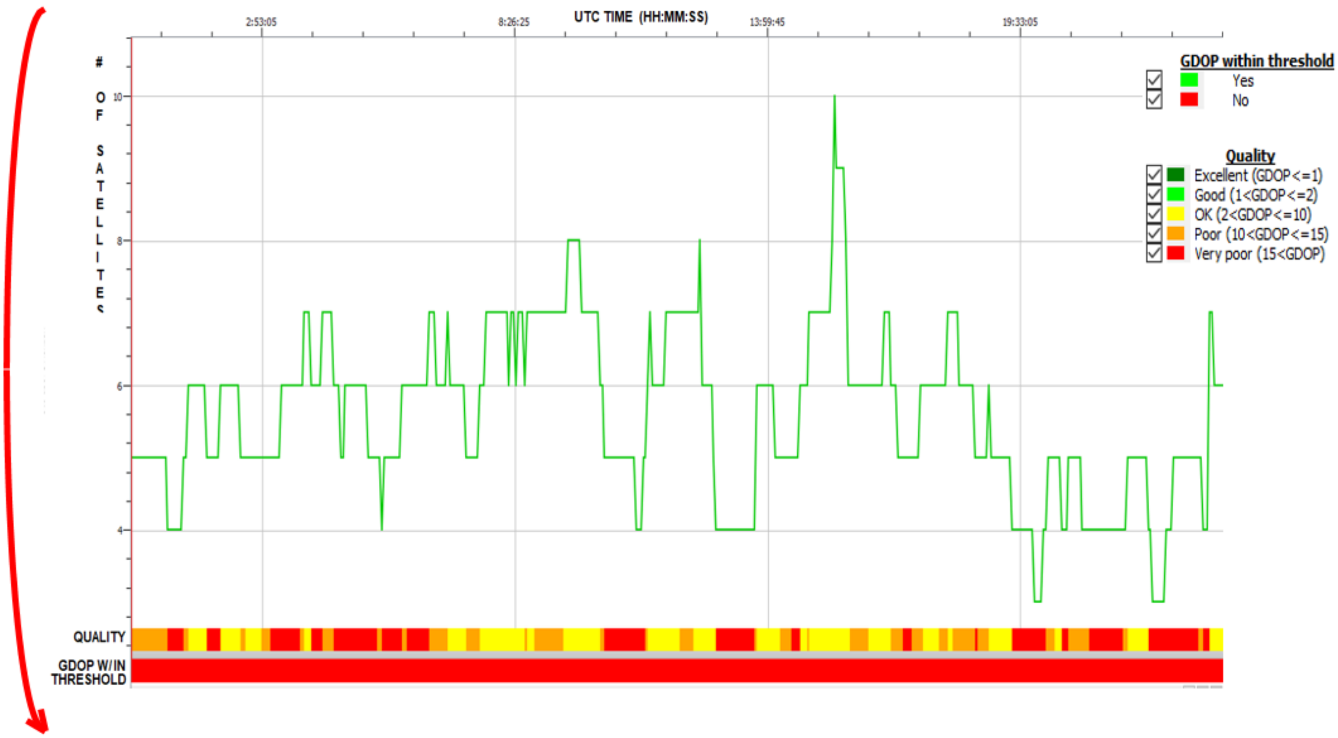


Figure C3. # GPS + Galileo satellites within a 24-hour 9-degree view

GPS + Galileo + GLONASS Satellites Within a 24-hour 9-degree View
1/2 Hemisphere View – at EOT

Coordinates: [30.0719 N, 94.1558 W]

- While augmentation by GLONASS increases # observable satellites to > 4, GDOP remains marginal and thereby continues to degrade performance

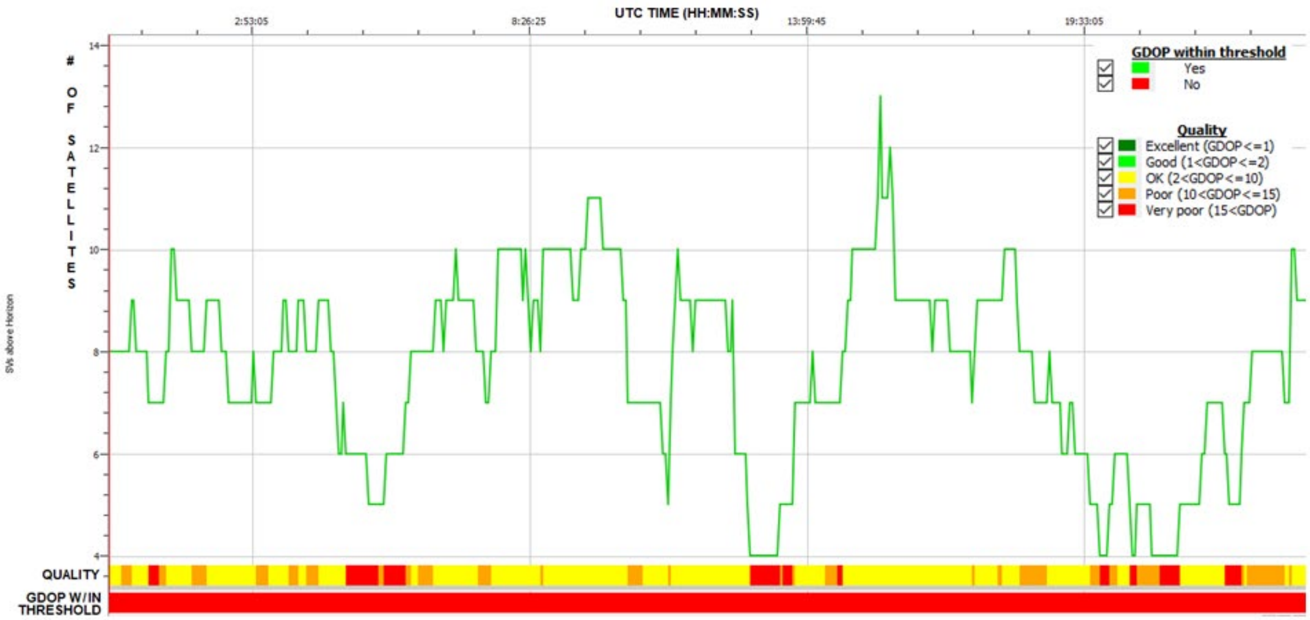


Figure C4. GPS + Galileo + GLONASS satellites within a 24 hour 9-degree view

UP EOT Field Test: uBlox AMY-6 GPS-only Receiver 1/2 Hemisphere View

Coordinates: [30.0719 N, 94.1558 W] → [30.072408 N, 94.1561 W]

- After discarding the initial 12,948 lines of zero-filled data
  $GPRMC,000000,V,0000.0000,S,00000.0000,W,0.0000,0.000,000000,,*35
  $GPGSA,A,1,,*32
- We obtain a discernable number of satellite cases = 3
  # Satellites=3 = 110 Percent= 0.4
  # Satellites=4 = 1,100 Percent= 3.5
  # Satellites=5 = 2,726 Percent= 8.8
  # Satellites>5 = 2,7182 Percent = 87.3

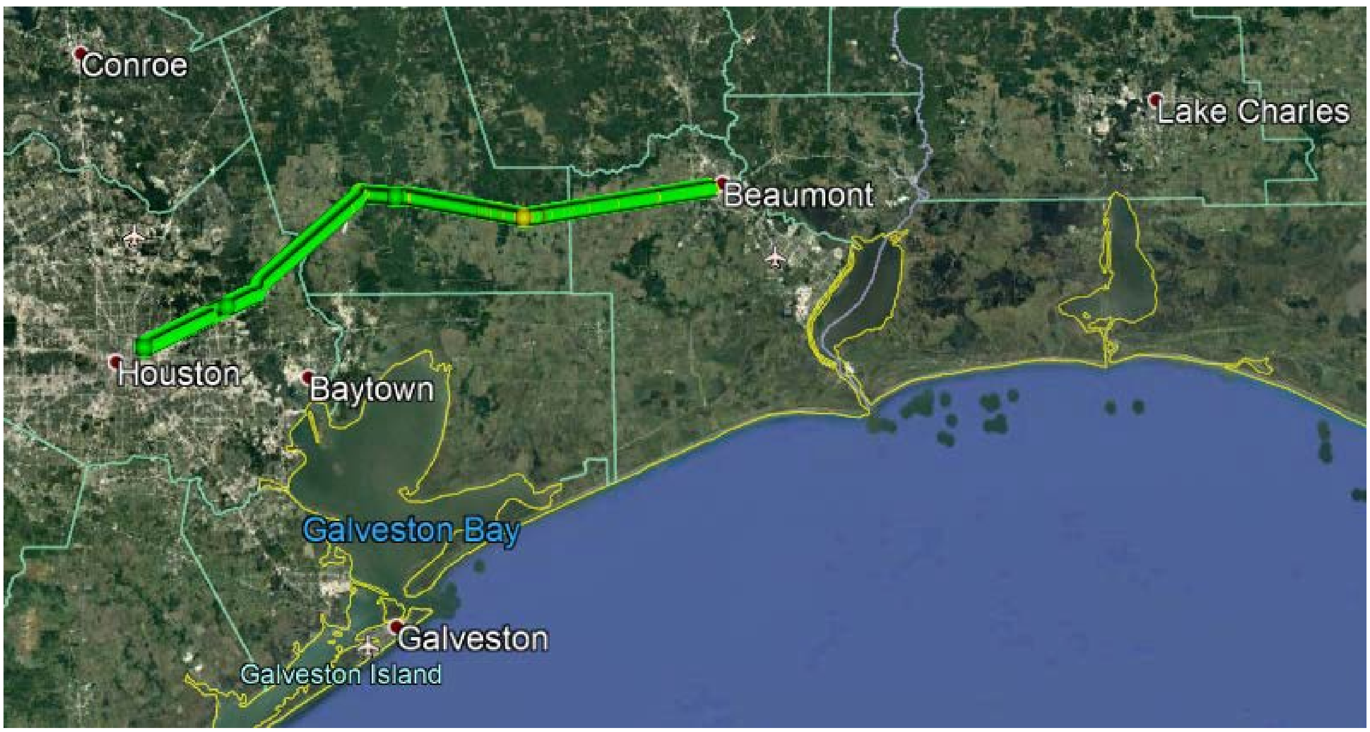


Figure C5. UP EOT Field Test: uBlox AMY-6 GPS-only receiver, 1/2 hemisphere view

UP EOT Field Test: uBlox AMY-6 GPS-only Receiver 1/2 Hemisphere View

Coordinates: [30.0719 N, 94.1558 W] → [30.072408 N, 94.1561 W]

- HDOP is plotted over the test trajectory.
- HDOP = Horizontal DOP (i.e., distortion in X and Y but not Z dimensions)
- A significant number of unacceptable HDOP instances are observed.

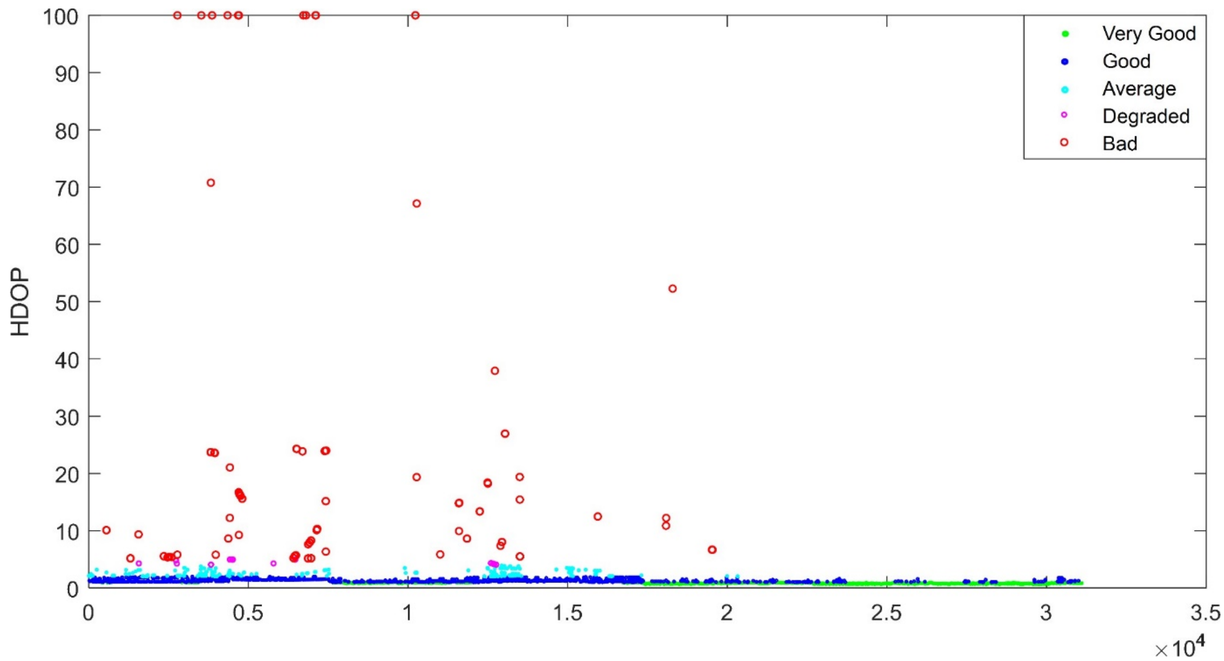


Figure C6. UP EOT Field Test: uBlox AMY-6 GPS-only receiver, 1/2 hemisphere view

Conclusions

- For HOT operation, full hemisphere visibility results in a mean of 18 GPS + Galileo Satellites and high quality GDOP yielding measurement error standard deviations meeting or exceeding manufacturer specifications.
- By contrast, EOT operation at 1/2 hemisphere reduced visibility results in a discernable number of cases where the number of GPS + Galileo Satellites are insufficient to determine EOT position.
- Moreover, EOT operation at 1/2 hemisphere reduced visibility consistently yields significantly degraded GDOP and HDOP quality that significantly affects usability of GNSS receiver data due to increased error standard deviation σ.
- **For example**, a uBlox receiver characterized by 2.5 m σ will degrade to on the order of 5.0m σ due to degraded GDOP and HDOP quality resulting in an increase of 10 nines safety distance from 53 feet to 109 feet (2 car lengths).
- **Conclusion**: A low cost, standalone GNSS solution is insufficient to provide high availability and accurate clearance assurance range over the full scope of operational scenarios.

Appendix D.
PTL EOT Segment Requirements

Positive Train Location End-of-Train Segment Requirements

Date: 2019

Modified Date: 2019

Prepared by

Transportation Technology Center, Inc. (TTCI)

55500 DOT Road

Pueblo, CO 81001

REVISION HISTORY

Revision Level	Date	Description	Revised by
1.0	12/2016	Initial Release	TTCI
1.1	9/2019	Revised PTL EOT requirements	TTCI

1 Background

Positive Train Control (PTC) is a technology designed to automatically stop a train before certain types of accidents occur. PTC is intended to keep a train within authorized limits on a track and under its speed limit. To accomplish this, movement authorities and speed limits are electronically transmitted to the train. PTC systems track the train position relative to these limits and employ predictive braking enforcement algorithms to automatically bring the train to a safe stop before violating a limit. PTC is designed to prevent train-to-train collisions, over-speed derailments, unauthorized incursions into established work zones, and movement of a train through a main line switch in the wrong position. The Rail Safety Improvement Act of 2008 [2] mandates installation of interoperable PTC on all main lines with regularly scheduled intercity passenger or commuter service, and on all main lines over which poisonous or toxic-by-inhalation hazardous materials are transported.

Most PTC systems rely on Global Positioning System (GPS) to identify the location of the controlling locomotive of a train. The location of the rear of the train is then derived from the location of the lead locomotive using the train length typically provided by the railroad's management information systems (MIS) and confirmed or updated by the locomotive engineer. The MIS train length is an approximation and is not considered to be reliable enough by itself to determine the actual length of the train. Train length is critical data that needs to be dependable, as operating performance and safety can be affected when truncating or releasing movement authorities behind a train, especially in dark (unsignaled) territory. In addition, the GPS-based location used by PTC systems does not provide a sufficient level of accuracy to perform track level discrimination under all conditions.

Train location is a key input for PTC systems to effectively track against authority limits and speed restrictions along the train route, and to enforce those limits and restrictions when necessary. While GPS data is typically used to collect this information in most PTC systems, under some conditions the PTC system could benefit from higher accuracy location determination. The Federal Railroad Administration (FRA) funded a research and development program executed by Transportation Technology Center, Inc. (TTCI) to develop the requirements for Positive Train Location (PTL) and to develop a system that meets these requirements.

Improved accuracy of location determination will provide more reliable location data to the PTC onboard system for dependable track discrimination, especially important during initialization in multiple-track territory. The ability to locate the locomotive and the rear end of a train with greater accuracy, in conjunction with other enhancements, will permit the railroads to explore options to improve the operational reliability of the PTC system.

2 Applicable Documents

The following documents apply to these system requirements:

1. Code of Federal Regulations 49, Part 236 Subpart I
2. Code of Federal Regulations 49, Part 236 Subpart H
3. AAR Manual of Standards and Recommended Practices, Section K, Standard S-5701, “End-of-train Communications,” Revised 2009
4. AAR Manual of Standards and Recommended Practices, Section K, Standard S-5702, “Railroad Electronics Environmental Requirements,” Revised 2009
5. Relevant Interoperable Train Control (ITC) Standards – will be provided at a later date under a Non-Disclosure Agreement
6. AAR Manual of Standards and Recommended Practices, Section K, Standard S-9101, “Locomotive Electronics System Architecture,” Adopted 2012
7. AAR Manual of Standards and Recommended Practices, Section K, Standard S-9354, “Edge Message Protocol Specification,” Adopted 2010
8. AAR Manual of Standards and Recommended Practices, Section K, Standard S-9355, “Class C Messaging Specification,” Adopted 2010
9. AAR Manual of Standards and Recommended Practices, Section K, Standard S-9356, “Class D Messaging Specification,” Adopted 2010

3 System Overview

3.1 System Objectives

Most PTC systems rely on GPS-based location systems to identify the location of the locomotive of a train. The location of the rear of the train is then derived by the onboard system from the location of the locomotive using the train length typically provided by the railroad's management information systems (MIS). The MIS train length is an approximation and is not necessarily reliable enough to use to determine the actual length of the train for safety purposes. Train length data needs to be dependable, as operating performance and safety can be affected when releasing movement authorities behind a train, especially in dark territory. In addition, the current level of GPS-based location accuracy utilized by PTC systems does not provide a sufficient level of accuracy to perform track level discrimination under all conditions. Conditions that have presented a challenge to PTC systems include positive location determination at system initialization, specifically track discrimination when the train initializes in multi-track territory, and tracking the train location when GPS is unavailable for some distance, such as in tunnels and in mountainous or urban canyons.

The objective of this system is to provide an ITC-compliant PTC locomotive onboard system with the positive locations of both the locomotive and of the rear of the train at the required accuracy under all conditions. The PTL system will also provide speed and direction of movement to the locomotive onboard system.

3.2 PTL System Description

The PTL system is a locomotive onboard and off-board sub-system that interfaces with an ITC-compliant PTC locomotive onboard system to provide high accuracy locations of the locomotive and of the rear of the train, train speed and direction of movement. The PTL system will provide location input to the PTC locomotive onboard system which will derive the train length from this data.

It is expected that the PTL system location algorithm will use geodetic coordinates, internal sensors and optionally locomotive-based sensor data (to be defined by the vendor). The PTL location algorithm will consolidate information and calculate the location of the locomotive and rear of the train. Once the train location has been determined initially, the PTL system is required to report the locations of the locomotive and rear of the train, including during temporary unavailability of GNSS and communication failure between the locomotive onboard and end of train PTL components. The PTL system will also monitor and report the health and communication status of its locomotive onboard and end-of-train components to the PTC systems management system.

Note that even though use of GNSS is expected, other positioning methods with clearly shown potential of meeting the requirements will be considered.

3.3 Conceptual Architecture

The diagram below is a conceptual representation of the PTL system in its final stage after complete integration with an ITC-compliant PTC locomotive onboard system. The architecture is based on the assumption that GNSS may need to be augmented by additional sensors to develop a real-time location solution for the rear of the train.

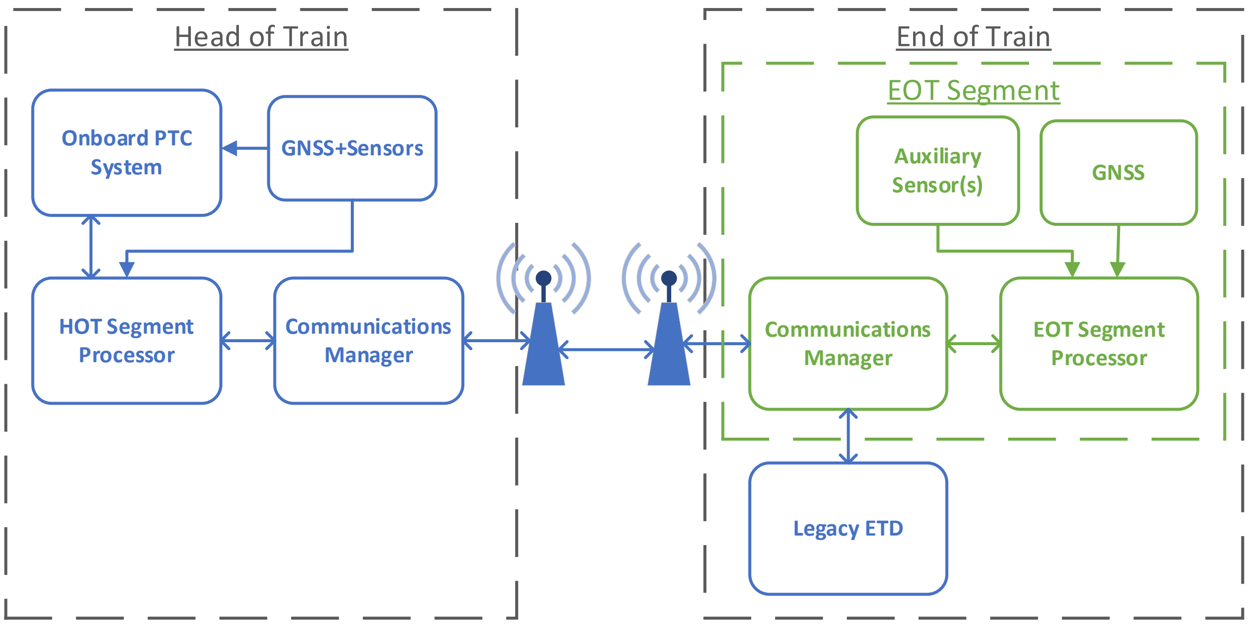


Figure D1. Conceptual architecture

4 Functional Requirements

PTL EOT 01(a) The PTL EOT segment shall report to the PTL HOT segment the geodetic position of the rear-of-train when the rear-of-train is moving.

PTL EOT 01(b) The PTL EOT segment shall report to the PTL HOT segment the geodetic position of the rear-of-train when the rear-of-train is stationary.

PTL EOT 01(c) The PTL EOT segment shall report to the PTL HOT segment the along-track distance of the rear-of-train relative to the nearest Track Point of Interest (TPOI) when the rear-of-train is moving.

Note: this requirement applies to a TPOI that is beyond (not under) the train.

PTL EOT 01(d) The PTL EOT segment shall report to the PTL HOT segment the along track distance of the rear-of-train relative to the nearest detected TPOI when the rear-of-train is stationary.

Note: This requirement applies to a switch that is beyond (not under) the train.

PTL EOT 02 The PTL EOT segment shall include all geodetic and relative position reports within the same message.

PTL EOT 03(a) The PTL EOT segment shall report to the PTL HOT segment the 1-sigma along-track uncertainty values associated with each report of the geodetic position of the PTL EOT segment.

PTL EOT 03(b) The PTL EOT segment shall report to the PTL HOT segment the 1-sigma across-track uncertainty values associated with each report of the geodetic position of the PTL EOT segment.

PTL EOT 03(c) The PTL EOT segment shall report to the PTL HOT segment the 1-sigma along-track uncertainty value associated with each report of the along track-distance of the PTL EOT segment relative to the nearest detected TPOI.

PTL EOT 04 The PTL EOT segment shall provide to the PTL HOT segment a time stamp with every report.

PTL EOT 05 The PTL EOT segment shall use readily available free external wireless position reference signals only, as well as those that may be optionally broadcast by a railroad.

PTL EOT 06(a) The PTL EOT segment shall monitor for any failure of a PTL EOT sensor(s).

PTL EOT 06(b) Within the existing EOT segment position report, the PTL EOT segment shall report to the PTL HOT segment failure of any PTL EOT sensor upon detection of the failure.

PTL EOT 07(a) The PTL EOT segment shall monitor the PTL HOT segment the number of GNSS satellites visible per constellation: GPS, SBAS, Galileo, GLONASS and BeiDou.

PTL EOT 07(b) Within the existing EOT segment position report, the PTL EOT Segment shall report to the PTL HOT segment the number of GNSS satellites visible per constellation: GPS, SBAS, Galileo, GLONASS and BeiDou.

PTL EOT 07(c) The PTL EOT segment shall log any failure of a PTL EOT segment component.

Note: EOT segment components include the sensor(s) and the radio(s).

PTL EOT 08 The PTL EOT segment shall report its geodetic coordinates to the PTL HOT segment as Latitude, Longitude and Altitude of position.

PTL EOT 09 The PTL EOT segment shall provide an interface for operators and maintainers to directly perform configuration at the PTL EOT segment.

PTL EOT 10 The PTL EOT segment shall provide an interface for operators and maintainers to directly perform diagnostics at the PTL EOT segment.

PTL EOT 11 The PTL EOT segment shall provide an interface for operators and maintainers to directly perform manual pairing at the PTL EOT segment in the event of failure of autonomous pairing with a PTL HOT segment.

PTL EOT 12 The PTL EOT segment shall include a Comms Manager.

PTL EOT 13(a) The PTL EOT segment shall interface with the ETD segment through a shared Comms Manager.

PTL EOT 13(b) In coordination with the PTL HOT Segment, the PTL EOT segment Comms Manager shall select the radio (when more than one is available) to communicate with the PTL HOT segment.

PTL EOT 13(bb) In coordination with the PTL HOT segment, the PTL EOT Segment Comms Manager shall select the RF band and channel (when more than one is available) to communicate with the PTL HOT segment.

PTL EOT 13(c) The PTL EOT segment shall accept all legacy ETD segment messages from the ETD segment.

PTL EOT 13(d) The PTL EOT segment Comms Manager shall route messages among the PTL EOT segment sensor/processor suite, ETD segment, and radios.

PTL EOT 14 The PTL EOT segment shall allow for autonomous pairing with the PTL HOT segment in the presence of other active PTL HOT and EOT segments that may or may not be in the process of pairing.

PTL EOT 15 The PTL EOT segment shall be capable of determining relative distance from the following Track Points of Interest (TPOI): switch points, crossing diamond, highway grade crossing.

PTL EOT 16 The PTL EOT segment shall be self-powered or derive power from the ETD segment.

PTL EOT 17 The rate at which the PTL EOT segment reports position to the PTL HOT Segment shall be dynamically configurable by command from the PTL HOT segment.

PTL EOT 18 The rate at which the PTL EOT segment reports distance relative to a TPOI to the PTL HOT segment shall be dynamically configurable by command from the PTL HOT segment.

5 Performance Requirements

PTL EOT 19(a) Subject to availability of sufficient GNSS signals to compute an EOT segment position, velocity, time (PVT) solution, the along-track accuracy with which the PTL EOT segment reports the rear-of-train geodetic position shall be ≤ 25 meters Time-Based Reference (TBR) at a confidence level ≥99.999999997%.

Note: This requirement applies at the time of PTL EOT segment position reporting.

PTL EOT 19(b) While the train is traveling at ≤ 20 mph within a distance of 100 feet from a TPOI, the error with which the PTL EOT segment reports the PTL EOT segment along-track distance relative to the detected TPOI center shall be no greater than 5" per 5' (TBR) of distance from the TPOI.

Note: This requirement applies at the time of PTL EOT segment location reporting in regard to a TPOI that is beyond (not under) the train.

PTL EOT 19(c) While the train is traveling ≤ 20 mph, the PTL EOT segment shall determine (in conjunction with the PTL HOT segment) which track the end of the train is occupying with a confidence level of 99.999999997%.

Note: this requirement applies at the time of PTL EOT segment position reporting.

PTL EOT 20 The PTL system shall be interoperable with the Next Generation EOT-to-HOT radio and messaging system architecture.

Note: This requirement will be further refined when more information becomes available about the Next Generation EOT-to-HOT radio and messaging system.

PTL EOT 21(a) During reverse movement, and when the train is traveling ≤ 20 mph, the rate at which the PTL EOT segment reports its geodetic position to the PTL HOT segment shall nominally be once every 4 seconds (TBR), configurable from 1 sec to 60 sec.

PTL EOT 21(b) During reverse movement, and when the train is traveling ≤ 20 mph, the rate at which the PTL EOT segment reports its along-track distance from a detected TPOI shall nominally be once every 4 seconds (TBR), configurable from 1 sec to 60 sec.

PTL EOT 22(a) During forward movement, the rate at which the PTL EOT segment reports its geodetic position shall nominally be once every 16 seconds (TBR), configurable from 1 sec to 300 sec.

PTL EOT 22(c) During forward movement, the rate at which the PTL EOT segment reports its along-track distance from a detected TPOI shall nominally be once every 16 seconds and configurable from 1 sec to 300 sec.

PTL EOT 23 Subject to availability of sufficient GNSS signals to resolve an EOT segment position, the PTL EOT segment shall report a geodetic position within 1 minute of system initialization.

Note: Refer to requirement 36(a) for the associated accuracy requirement.

6 Physical Requirements

PTL EOT 24 The PTL EOT segment shall comply with the environmental requirements for "Vehicle Exterior (Body Mounted)" devices, as defined in the AAR Manual of Standards and Recommended Practices, Section K, Part V, Standard S-9401, "Railroad Electronics Environmental Requirements," Revised 2014.

PTL EOT 25 The PTL EOT segment shall be integrated into the train EOT.

PTL EOT 26(a) For self-powered units, the PTL EOT segment shall be capable of uninterrupted operation for at least 36 hours.

PTL EOT 26(b) For units deriving power from the ETD, the PTL EOT segment shall have a backup battery capable of sustaining uninterrupted operation for at least 12 hours.

PTL EOT 27 The total weight of the PTL EOT segment integrated into the ETD shall comply with MSRP K-II, S-9152.

PTL EOT 28 Attachment, detachment and connection of the combined PTL EOT and ETD segments to the last railcar shall be possible within 1 minute when wearing gloves.

PTL EOT 29 The design of the PTL EOT segment shall facilitate replacement of failed components by trained railroad personnel (removal/connection of modular components).

7 Reliability, Availability, and Maintainability (RAM)

PTL EOT 30 The PTL EOT segment equipment shall have a Mean Time Between Functional Failures (MTBFF) of no less than to be determined (TBD) hours.

PTL EOT 31 The PTL EOT segment equipment shall have a Mean Time Between Failures (MTBF) of no less than TBD hours.

PTL EOT 32 The PTL EOT segment equipment shall be designed for a design life of at least TBD years.

PTL EOT 33 The PTL EOT segment equipment shall have a total system availability of 99.99% in revenue service configuration, as calculated below.

Note: System availability (A_s) as is defined as the probability that a system is capable of operating at a random point in time. A_s depends upon Mean Time Between Functional Failures (MTBFF), Mean Time to Repair (MTTR), and Mean Repair Travel Time (MRTT), and can be expressed as:

$$As = \frac{MTBFF}{MTBFF + MTTR + MRTT}$$

PTL EOT 34 The PTL EOT segment shall be designed such that trained railroad personnel are able to replace a failed unit.

PTL EOT 35 The mean time to diagnose and replace a failed PTL EOT segment component by trained railroad personnel shall be no more than 30 minutes.

PTL EOT 36 The PTL EOT segment shall provide a means to perform software diagnostics.

Appendix

This appendix identifies the verification method(s) to be used by TTCI to verify that the PTL system satisfies the Phase I and Phase II requirements.

Industry-accepted verification methods are defined as follows:

- **Inspection**: defined as a visual verification that existing data, components, equipment and installations conform to the specifications to which they were produced. This method is used to verify that the system/subsystem meets those requirements that cannot be demonstrated through operational testing. It includes examination of hardware and software design documentation and diagrams. These requirements include hardware and software configuration and adherence to engineering, programming and design standards. Inspections do not require components or equipment to be operating.
- **Analysis**: defined as the evaluation of data using analytical techniques such as equations, formulas, statistics, charts, simulation and/or probability theory to verify that a specified requirement has been met. Success is determined by showing that an independent computation of expected results/outputs match the actual operation results. It is used to validate operations whose results are not directly related to input.
- **Demonstration**: defined as an aural/visual observation of the performance of the system within a controlled environment. It provides for the verification in real-time of discrete functions, such as indicators turn on or off, alarms sounded, displays varied, and so on.
- **Test**: defined as an instrumented or non-instrumented test of components, equipment or installations to verify that a specified requirement has been met where success is determined by observing the real-time results of the test or by performing post-test data reduction or data analysis, where the observed results match the expected results for a given known input.
- **Comparison**: defined as a comparison of the operation of the new system, segment, or subsystem element with a known standard, followed by an analysis of results.
- **Usage**: defines as the repeated execution of the system in conjunction with one or more of the methods described above.

Appendix E.
Alternative EOT Segment Architecture

Table E1. Alternative EOT segment architecture

Cost *Notional*	Sensors	Estimated Quantity Cost *(10K units)*	Position Error Cross Track σ with GNSS *(cm)*	Position Error Along Track σ with GNSS *(cm)*	Speed Measurement σ without GNSS *(mph)*	L/R Direction Change Through Switch Detection
4$	High End GNSS/**RTK** Rx (50 cm σ) Quality RTK GNSS Antenna Night/Day Sensor CPU Accelerator Tactical IMU	$3,800	40 1	46 1	0.1	YES
3$	Moderate End GNSS Rx (75 cm σ) Quality GNSS Antenna Night/Day Sensor CPU Accelerator Tactical IMU	$1,800	59	69	0.1	YES
2$$	Low End GNSS/**RTK** with IMU (150 cm σ) Low Cost GNSS Antenna Night/Day Sensor CPU Accelerator	$1,200	119 1	138 1	0.3	YES
2$	Low End GNSS with IMU (250 cm σ) Low Cost GNSS Antenna Night/Day Sensor CPU Accelerator	$1,000	198	231	0.3	YES
1$$	Low End GNSS/**RTK** with IMU (150 cm σ) Low Cost GNSS Antenna	$500	119 1	138 1	Detects Pull Apart but no independent speed measurement	NO
1$	Low End GNSS with IMU (250 cm σ) Low Cost GNSS Antenna	$300	208	243	Detects Pull Apart but no independent speed measurement	NO

Cost	PTL System (EOT+HOT) **C-01a** Determine Relative Position of EOT Along Track and Proximity to POI with GNSS	PTL System (EOT+HOT) **C-01b** Determine Relative Position of EOT Along Track and Proximity to POI without GNSS	PTL System (EOT+HOT) **C-02a** EOT Track Discrimination with GNSS	PTL System (EOT+HOT) **C-02b** EOT Track Discrimination without GNSS	PTL System (EOT+HOT) **C-03a** Determine EOT Speed with GNSS	PTL System (EOT+HOT) **C-03b** Determine EOT Speed without GNSS	PTL System (EOT+HOT) **C-04** Estimate EOT Position After Reinitialization While in Motion (GNSS Required)	PTL System (EOT+HOT) **C-05** Estimate EOT Position Confidence GNSS / Camera at 1.2 M	PTL System (EOT+HO **C-06** Determine Train Integrit (EOT BPP, Train Length Speed Delta)
4$	✓ Error Growth ~ 5"/10' for 36' with σ=46cm after w/o RTK σ=1cm: with RTK ❶	✓ Error Growth ~ 5"/10'	✓ Imagery ~100% confidence	✓ Imagery ~100% confidence	✓ σ ~ 0.07 mph	✓ σ~ 0.2 mph	✓ σ < 50cm at boot with rapid drop to ~ 40cm xtrack ~ 46 cm along track σ=1cm: with RTK ❶	✓ GNSS[Xtrk =99.7%,Atrk=99.1%] Cam[Xtrk~100%, Atrk~5cm]	✓ *Train Length Monitor BPP Δ EoT/HoT Speed*
3$	✓ Error Growth ~ 5"/10' for 54' with σ=69cm thereafter	✓ Error Growth ~ 5"/10'	✓ Imagery ~100% confidence	✓ Imagery ~100% confidence	✓ σ ~ 0.1 mph	✓ σ~ 0.2 mph	✓ σ < 75cm at boot with rapid drop to ~ 59cm xtrack ~ 69 cm along track	✓ GNSS[Xtrk =96%,Atrk=92%] Cam[Xtrk~100%, Atrk~5cm]	✓ *Train Length Monitor BPP Δ EoT/HoT Speed*
2$$	✓ Error Growth ~ 5"/10' for 36' with σ=138cm after w/o RTK σ=1cm: with RTK ❶	✓ Error Growth ~ 5"/10'	✓ Imagery ~100% confidence	✓ Imagery ~100% confidence	✓ σ ~ 0.1 mph	✓ σ~ 0.2 mph	✓ σ < 150 cm at boot with drop to ~ 119 cm xtrack ~ 138cm along track σ=1cm: with RTK ❶	✓ GNSS[Xtrk =69%,Atrk=62%] Cam[Xtrk~100%, Atrk~5cm]	✓ *Train Length Monitor BPP Δ EoT/HoT Speed*
2$	✓ Error Growth ~ 5"/10' for 182' with σ=231cm thereafter	✓ Error Growth ~ 5"/10'	✓ Imagery ~100% confidence	✓ Imagery ~100% confidence	✓ σ ~ 0.1 mph	✓ σ~ 0.2 mph	✓ σ < 250 cm at boot with drop to ~ 198 cm xtrack ~ 231 cm along track	✓ GNSS[Xtrk =46%,Atrk=40%] Cam[Xtrk~100%, Atrk~5cm]	✓ *Train Length Monitor BPP Δ EoT/HoT Speed*
1$$	**No Capability do detect POI without N/D sensor**	*Very high drift due to no speed sensor*	58% confidence w/o RTK ~100% confidence with RTK	NF	✓ σ ~ 0.1 mph	✓ Speed Change Only	✓ σ < 150 cm at boot with drop to ~ 119 cm xtrack ~ 138cm along track σ=1cm: with RTK ❶	✓ GNSS[Xtrk =69%,Atrk=62%]	✓ *Train Length Monitor BPP Δ EoT/HoT Speed*
1$	**No Capability do detect POI without N/D sensor**	*Very high drift due to no speed sensor*	43% confidence w/o RTK ~100% confidence with RTK	NF	✓ σ ~ 0.1 mph	✓ Speed Change Only	✓ σ < 250 cm at boot with drop to ~ 208 cm xtrack ~ 243cm along track	✓ GNSS[Xtrk =44%,Atrk=38%]	✓ *Train Length Monitor BPP Δ EoT/HoT Speed*

RTK is likely to exhibit very low availability at the EOT

Table E2. Dead Reckoning

DR	Dead Reckoning
mod	moderate
AT	Along Track
CT	Cross Track
EoT	End of Train
ETD	End of Train Device
GPU	Graphics Processor Unit

Table E3. Key for table

	Level of Performance
	Excellent
	Good
	Acceptable
	Marginally Acceptable
	May be Unacceptable
	Unacceptable

Table E4. Additional notes

NOTES
1) EOT positioning performance is based upon PTL Phase Iia.2 Test Report - 20131106 EOT test results
2) Column D ROM prices are for purpose of relative technology pricing and may not reflect actual costs
3) Significant NRE is required to port imaging & pattern recognition algorithms to CPU + GPU NRE cost is NOT reflected in the cited prices for camera & radar processing solutions
4) Candidate cameras have not yet been validated to comply with AAR Environmental Specifications
5) All camera-based designs include a CPU+GPU capable of accommodating image processing at the EOT
6) C-15 applies to ETD geo-location used for inventory tracking only with a low rate position data rate
7) PTL EOT device is integrated into the ETD as a separate hardware package and presumes availability of ETD resident components such as pressure sensor, battery, housing and radio

Appendix F.
PTL EOT Development and Testing

1. PTL EOT Phase II PathForward

Positive Train Location (PTL) End-of-Train (EOT) Phase I established recommendations for an EOT sensor architecture. While alternative sensor technologies are believed to be applicable to EOT track feature detection, identification and relative positioning, the Phase II effort will focus upon camera system deployment. Empirical test with a selected day/night camera system will validate and refine as necessary proposed Phase I goal performance requirements.

While auxiliary-aiding of a low cost Global Navigation Satellite System (GNSS) receiver + embedded or independent Inertial Measurement Unit (IMU) represents the candidate solution approach, many environmental issues remain in question. Consequently, it is recommended that Phase II testing include a more comprehensive sensor suite to acquire on track data. Then by method of post data acquisition playback, specific sensors can be "detuned" to emulate lesser performance devices. This effort may be accomplished at minimal program expense by leveraging existing Precision Navigation Module (PNM) devices presently implemented as locomotive Head-of-Train (HOT) systems hosting navigation solution software. Moreover, since the EOT component must operate in concert with its companion HOT, additional HOT PNM software upgrades will be performed to realize full HOT/EOT system functionality.

Table F1. Available assets for EOT testing

Site	Description	Subcomponents & Details	Cost
HOT	Precision Navigation module	GNSS Rx + RTK	$0
		IMU	$0
		Antenna	$0
		Cabling	$0
	Radio	Multi-band	$0
EOT	Precision Navigation module	GNSS Rx + RTK	$0
		IMU	$0
		Antenna	$0
		Cabling	$0
	Radio	Multi-band	$0
	Alternative day/night cameras	Mono/Stereo	$3,000

Table F1 identifies existing assets that may be directly applied to the TTCI EOT Phase II effort to substantially reduce program hardware development risk and cost. Development of vision-based relative positioning will require an additional investment of $165,000 to provide a test and analysis framework appropriate for Phase II investigation. Local and TTCI-hosted field testing, analysis, algorithm refinement and reporting will require an additional $130,000. A detailed task breakdown appears in Table F2.

Table F2. Task breakdown

Task Name	Task Description
HOT updates to accommodate EOT	NOTE: HOT will use existing Precision Navigation module
Track database reference	Incorporate TTCI track database into HOT. This will be used for EOT position references as well as normal HOT Dead Reckoning
HOT-to-EOT radio interface	Develop IP based interface to radio pair deployed at HOT and EOT
EOT message decryption	Extract time tagged EOT data from EOT

Task Name	Task Description
EOT track ID update based on switch direction data	By using the track database indexed by the most current EOT position and Track ID, procedure determines next track ID after EOT passes through a switch with provided information of Left or Right movement
EOT navigation solution position update based on EOT POI relative distance	After detecting a point of interest (POI surveyed switch or boundary), the EOT determines the relative distance from the switch to the current EOT position. This is presumed to be accomplished accurately with an approximate error degraded of 5" per 10" along track. Based upon the surveyed switch position and accurate relative distance traveled from the switch position, the HOT will update its estimates of EOT position. This procedure is presumed to be applicable to slow speeds (<TBD mph) corresponding to maneuvers such as moving from main track to siding. Higher speeds at road crossings are further presumed
HOT-to-EOT distance tracking	Based upon the current HOT and EOT position estimates, the straight-line distance is determined
Back propagation-based EOT positioning	Based upon the HOT to EOT straight line distance combined with the history of HOT positions acquired "in excess of" one train length, the EOT position is determined by propagating backward along track with the HOT until the HOT to EOT line of sight distance results. The resulting EOT position that this occurs at corresponds to the EOT absolute position estimate
EOT Positioning	
Camera identification and procurement	An appropriate night/day or SWIR camera will be identified and procured to support ETD testing
Incorporation of EDGE-based navigation solution into EOT	A HOT PTL module will be strapped to the ETD. Given the distance operational environment, the EOT navigation solution tune parameters will be adjusted to reflect the degraded EOT operational environment
Stereo camera visual odometry tailoring to EOT	A camera will be strapped to the ETD. A visual odometry algorithm will be developed for the camera to provide position along track from detected reference points of interest (switch, diamond, road crossing) in addition to speed
Incorporation of camera speed into EOT navigation solution	The EOT navigation solution will be updated to include the visual odometry based speed source

Task Name	Task Description
EOT navigation solution switch detection	Stereo camera images will be used to detect track features including: switch, diamond and road crossing. Alternative methods of pattern recognition to machine learning will be investigated to determine the most reliable and computationally efficient strategy
EOT navigation solution relative position estimation	Based upon detected POI position and visual odometry based speed, EOT along track distance from the POI is determined
Testing	
Local field testing + algorithm refinement	Road tests will be performed with the combined HOT/EOT radio system to validate system functionality and assess performance. Errors will be resolved and performance refined as feasible within a local environment
TTCI Field Test #1	The updated HOT/EOT radio system will be tested at TTCI
Algorithm refinement	Based upon TTCI test #1 data, the combined HOT/EOT system will be optimized and refined
TTCI Field Test #2	The optimized and refined HOT/EOT/radio system will be tested at TTCI
Algorithm refinement + operational readiness	Based upon TTCI Test #2 data, the combined HOT/EOT system will be further refined to operational fielding
Operational Track Test	The fieldable HOT/EOT/radio system will be tested upon operational track of a selected carrier over a varied environment. Ideally, testing would be conducted on a railroad's geo-car
Post-test analysis	The results of operational track testing will be analyzed in comparison to the corresponding track databases
Test report preparation	A final test report and viewing graph presentation summarizing final TTCI and operational test results will be prepared

Abbreviations and Acronyms

ACRONYMS	EXPLANATION
AARC	Alaska Railroad
AAR	Association of American Railroads
ATO	Automated Train Operation
BRCC	Belt Railway Company of Chicago
BER	Bit Error Rate
BPP	Brake Pipe Pressure
BNSF	Burlington Northern Santa Fe Railway
CN	Canadian National Railway
CFM	Close Following Moves
ConOps	Concept of Operations
EDT	End-of-Train Device
EOT	End-of-Train
FRA	Federal Railroad Administration
FMB	Full Moving Block
GDOP	Geometric Dilution of Precision
GPS	Global Positioning System
GNSS	Global Navigation Satellite System (also known as GLONASS)
HOTD	Head-of-Train Device
HOT	Head-of-Train
IMU	Inertial Measurement Unit
ITC	Interoperable Train Control
KCS	Kansas City Southern Railway
LOS	Line-of-Sight
MIS	Management Information System
MSRP	Manual of Standards and Recommendations Practices
MRTT	Mean Repair Travel Time
MTBF	Mean Time Between Failures
MTBFF	Mean Time Between Functional Failures
MTR	Mean Time to Repair
NMEA	National Marine Electronics Association
NGHE	Next Generation HOT/EOT

ACRONYMS	EXPLANATION
OS	Operational Scenario
POI	Points of Interest
PTC	Positive Train Control
PTCDP	Positive Train Control Development Plan
PTCSP	Positive Train Control Safety Plan
PTL	Positive Train Location
PVT	Position Velocity Time
PHA	Preliminary Hazard Analysis
QMB	Quasi Moving Block
RTK	Real Time Kinematic
RAM	Reliability, Availability, and Maintainability
RFP	Request for Proposal
ROM	Rough Order of Magnitude
SBAS	Satellite-based Augmentation System
SWIR	Short-wave Infrared
TAG	Technical Advisory Group
TBR	Time-Based Reference
TBD	To Be Determined
TPOI	Track Points of Interest
TTC	Transportation Technology Center
TTCI	Transportation Technology Center, Inc.
UP	Union Pacific Railroad
UC	Use Case