FUNCTIONAL SAFETY STRATEGIES FOR MODERNIZING SIGNALING SYSTEMS

JUNE 2022

INTRODUCTION

Piper Networks has an array of safety critical systems in service for the Rail & Transit industry which are designed to meet the requirements of transit operators engaged in both greenfield installations and brownfield upgrades to their signaling systems.

One prime example of this is Piper's vital Rail Positioning System (RPS) that uses Ultra Wideband (UWB) radio ranging to determine the precise location of trains throughout their territory with a variance of less than 10cm. The system has a variety of features that make it a safe, reliable, and cost effective replacement for traditional signaling equipment including roadbed transponders, undercarriage antennas, and wheel odometry. In this configuration, it is ready for integration with Communication Based Train Control (CBTC) deployments. And for operators that do not require the comprehensiveness of a CBTC system, RPS delivers critical functionality for Automatic Train Protection (ATP) requirements to support signaling.

This document describes the technical and commercial benefits of the RPS system. While not focusing in particular on individual train lines, it addresses design concerns as agencies seek to modernize their signaling programs for the future.

SIGNALING OPTIONS

Agencies have several options for the design of safe train control systems on various lines depending on the operational requirements of the system.

For many urban transit operators, Communication Based Train Control (CBTC) is an appropriate choice. CBTC has the potential to convert one or more lines from traditional track circuits protected by signals to a moving block design with cab signaling and Automated Train Operation (ATO). CBTC deployments are costly and have complex schedules for installation due to the Auxiliary Wayside System (AWS) infrastructure required. For example, the QBL East project in New York was awarded to a supplier for $346 million despite it being a relatively small segment of the NYCT subway system.

In a recent Market Sounding Query (MSQ) Transport for London (TFL) recently referred to CBTC upgrades as “big bang” investments. It’s an appropriate metaphor given the complexity of installation and the delays it can cause to current revenue systems. Should agencies determine that they do not need the improved headway benefit that CBTC affords, the agency may choose a design that retains fixed block separation and adds modern train protection systems that improve safety at a fraction of the cost of CBTC.

A fundamental requirement of any signaling system is safety certification to a CENELEC SIL-4 level. In CBTC, this vitality is achieved, in part, by meeting the Automatic Train Protection (ATP) functionality required for safe train operation as defined by the IEEE 1474.1 Standards for Communications-Based Train Control Performance and Functional Requirements.

For lines that do not rise to the CBTC level of requirements, agencies may choose a design based on signal protection that relies on traditional signaling with additional safety functions provided in an overlay design in order to upgrade and achieve SIL-4 operation. This approach is similar to how Positive Train Control (PTC) operates. The PTC system is effectively an ATP system overlaid on certain train lines regulated by the Federal Railroad Administration (FRA) to prevent overspeeds by train operators.

Before diving deeply into the differentiations between the CBTC and overlay approaches, it's helpful to describe how the RPS is designed and how it operates. This will establish a context for understanding the implementation requirements and overall benefits of the system.

This functionality includes:

- Train Location
- Train Speed Determination
- Safe Train Separation
- Overspeed Protection and Brake Assurance
- Rollback Protection
- End of Track / Limits Protection
- Parted Consist Protection / Coupling & Uncoupling of Trains
- Zero Speed Detection
- Door Opening Control Protection Interlocks
- Departure Interlocks
- Emergency Braking
- Route Interlocking
- Traffic Direction Reversal Interlocks
- Work Zone Protection
- Broken Rail Detection
- Restricted Route Protection

RPS DESIGN

In a railway application, the RPS is an uncomplicated design. There are two UWB radio types used in the system: carborne devices called tags and wayside devices called anchors. At a high level, train position is determined by the communication between the tag with two or more anchors at all times while the train is operating in the territory. To reach Piper's internal requirements for the safety function of vehicle localization and speed determination, the system is based on composite fail safe architecture.

The current spacing of the anchors along the wayside is primarily determined by track geometry - taking curve, grade, and elevation into consideration. While every system is different, an average spacing of 1000' will meet the availability goals of most high level safety targets. During the design process, Piper reviews the ranging data collected during surveys and performs simulations to determine the necessary spacing for a revenue system - ensuring that the configuration is resilient and provides continuous communication coverage even in the event of failed wayside anchors.

Tags are installed in each unit of the train. This provides unit coupling flexibility for car equipment departments and ensures that the tags can communicate with wayside anchors from both the front and rear of the train and helps minimize the number of anchors required for safe operation. The following illustration provides a comprehensive diagram of the RPS components and their integration with CBTC and Data Communication Systems (DCS) equipment. The train is represented in a multi-unit configuration - A1/B1/B2/A2 - with UWB communication occurring in the A1/A2 cars. The UWB in the B1/B2 cars are inactive in this configuration.

In an integration of the RPS into CBTC, the interaction between Piper wayside anchors mounted on the wayside and Piper tags installed on the vehicle facilitates the geolocation train. As it moves through the territory, distance is measured between anchors and tags using a calculation based on the Time-of-Arrival of the UWB radio pulse. Piper's navigational computers called tag controllers use the ranging data, the known positions of the anchors, and the database of the mathematical model of the track to compute the train's location. The RPS tag controller then produces a UDP packet, formatted to meet CBTC requirements, and injects the positioning and speed data into the Onboard Controller Unit (OBCU).

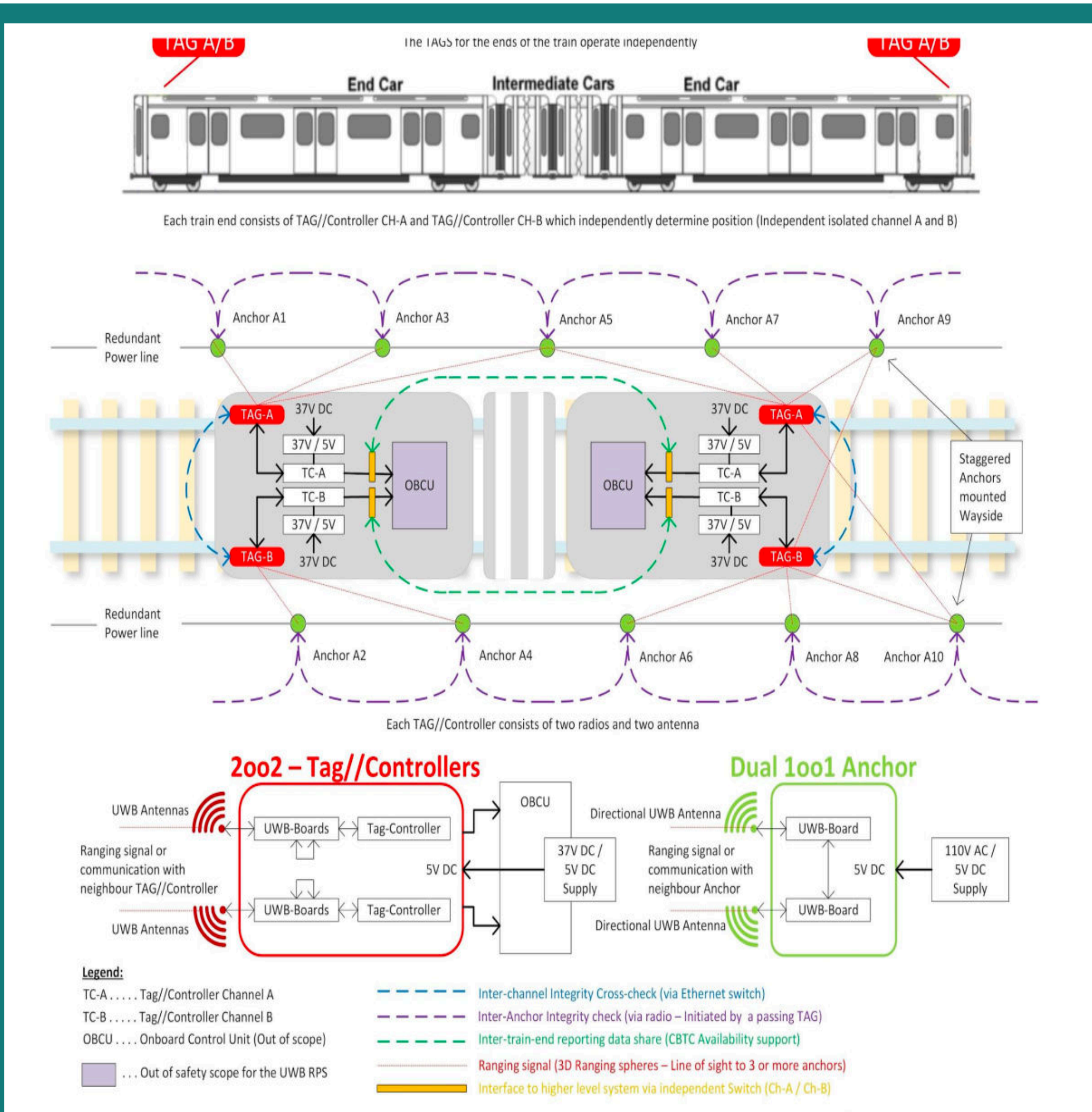
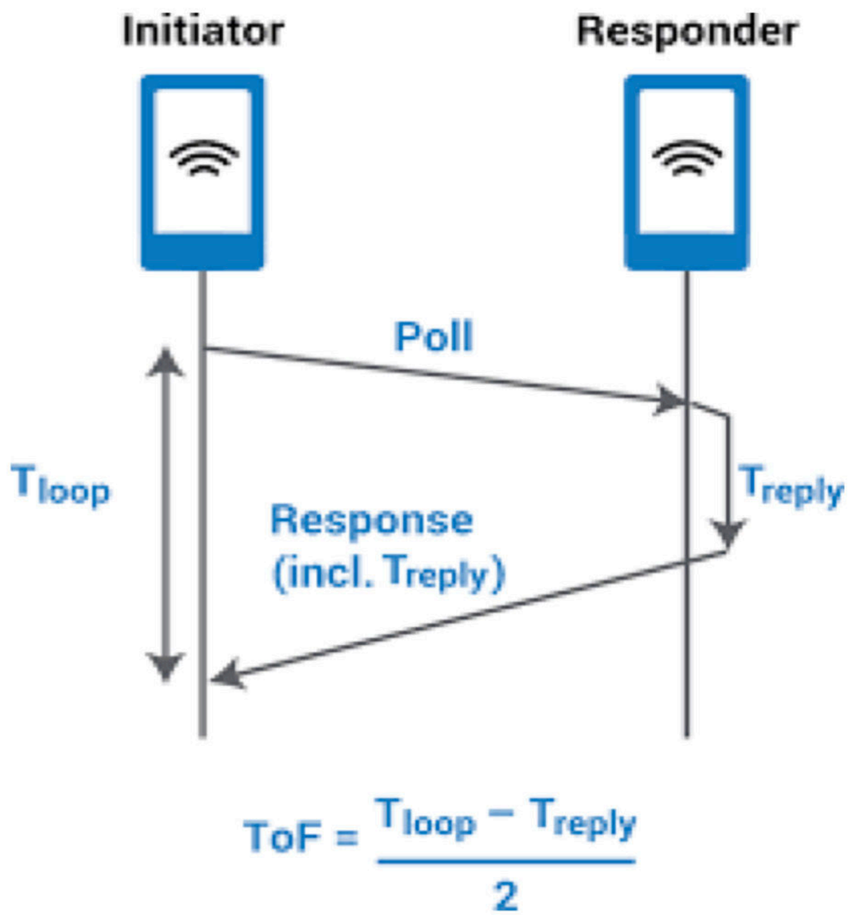


Figure 1 Piper Onboard Architecture

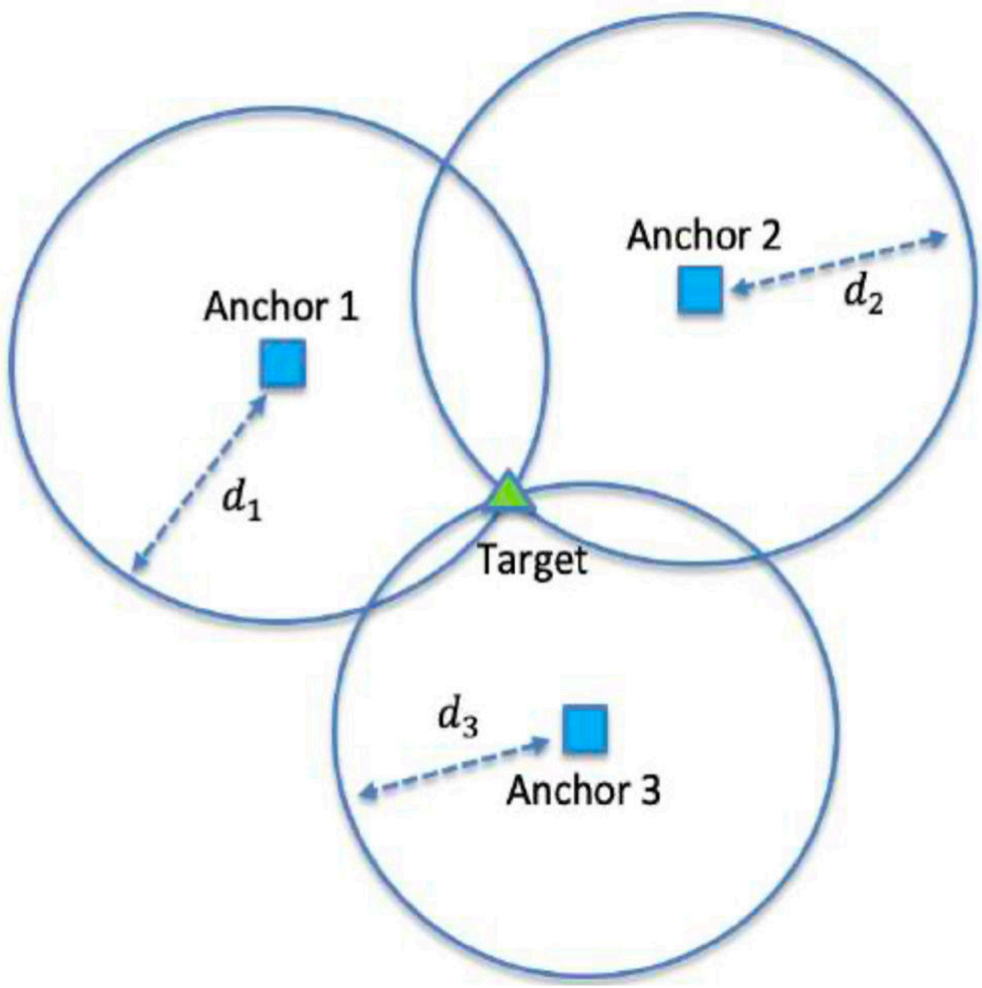
WHY UWB?

There are some misconceptions about Ultra Wideband technology that Piper seeks to address in this document. The first is that UWB navigation is a substitute for CBTC. It is not. The second is that it is a new and untested technology. Indeed, Ultra Wideband has been widely used for decades in military, mining, and industrial applications. Interest in UWB from the transportation industry is more recent, but it's important to highlight the reasons why the technology is safe and reliable for rail navigation.

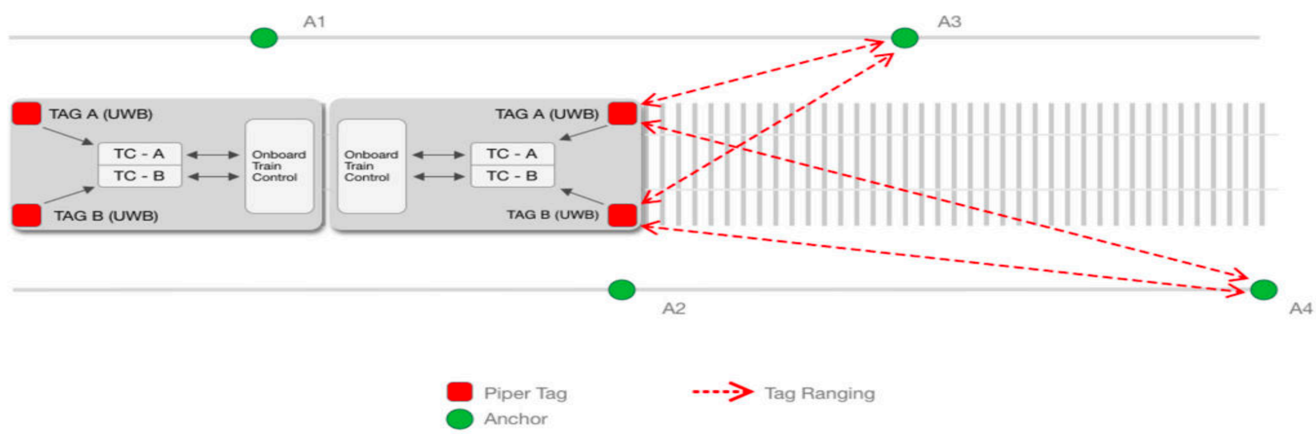


Positioning with radio ranging is a well established method. Most radios possess the physical properties capable of measuring distances between two transceivers.

What sets UWB apart from other radios in terms of positional accuracy is the unique combination of an exceptionally large bandwidth (500MHz) with micro pulse transmissions and the use of Time of Flight (ToF) calculations to determine precise distances. Piper's UWB radios have positional accuracy to within 10cm at high speeds. In an industrial real-time-positioning application of UWB, the system requires three or more radios to position an object in 3 dimensions, as illustrated below.



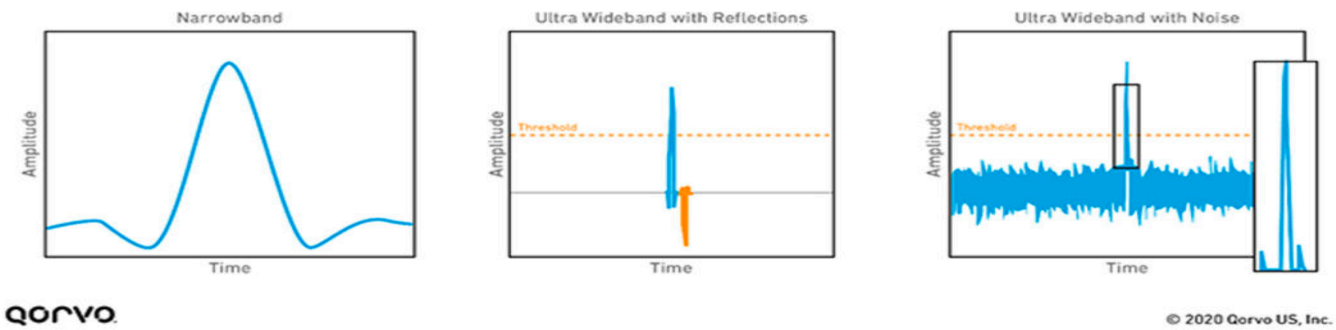
Because a railroad operates in 2 dimensions, only two reference positions are required to locate a train on a track. Reliability and availability are achieved with the ability of the carborne radio to communicate with multiple radios deployed on the wayside.



Railways are challenging physical environments for radio communication. Radio frequency signals in these conditions are susceptible to interference from structural reflections and environmental conditions. UWB is the only radio technology that can successfully mitigate these interference conditions.

- The 500MHz bandwidth of the UWB transmission ensures that if there is interference in one part of the band, it does not impact the entire spectrum.
- If there are reflections in the transmissions, the availability of the bandwidth overcomes any deteriorations.
- If there are poor environmental conditions, the bandwidth overcomes signal loss.

The illustration below shows a comparison of a narrow band WiFi signal compared with a UWB signal and highlights how UWB micro pulse transmissions overcome both reflections and channel noise.



In summary, UWB radios are highly reliable, deterministic devices for determining position and speed of trains in a railway territory. Piper has achieved SIL-4 certification in large part because its core data is not abstracted, extrapolated, nor derivative. Rather, it is based on speed of light calculations that are very close to the physical properties of the RPS UWB radios.

The next section of this document describes how individual UWB radios use these beneficial characteristics within a CBTC system.

CBTC INTEGRATION EXPERIENCE

Piper has completed integration testing with several CBTC suppliers including Hitachi, Thales, and Mitsubishi. We have practical experience in revenue applications including deployment on the Flushing Line (7 Train) and Canarsie Line (L Train) in the NYCT subway system. We are also currently contracted by NYCT to develop an interoperability specification for the MTA to ensure that when design specifications are issued for upcoming signaling initiatives, the agency has multiple suppliers available, all operating on the same standards and protocols for UWB communication.

Surveys and Databases

In order for the UWB system to operate as designed, it's essential to know the exact position of the wayside anchors. Piper performs two checks to ensure that this information is accurate. The first is an absolute positioning test using a GPS-RTK device that is temporarily attached to the anchor following installation. This determines the exact location of the anchor to within a few centimeters. The second is an "as-built" LiDAR scan of the territory, usually performed from an engineering or hyrail vehicle. Surveying in overbuilt areas or tunnels where GPS is not reliable is more involved. Piper will use available civil survey information and perform LiDAR-based measurements to complete the process.

With this information, and in combination with a track diagram obtained from the transit operator, Piper can build a database of the entire territory. This database is stored in the carborne tag controller and is shared by the CBTC system. As the train moves through the territory, the carborne UWB tag is in constant communication with several wayside UWB anchors. Because the RPS knows the absolute position of the anchors, the time-of-flight calculations made in real time position the train on the center line spline of the track with centimeter level accuracy.

Data Structures

The positioning data that Piper shares with the CBTC system has two fundamental values: edge and offset. Edge is the track segment the train is located within. It is defined as the segment of rail between switch points. Offset is defined as either the distance from the origination point of the edge or the territory, depending on how the CBTC system is designed.

Meeting Safety Requirements

Piper's goal is to provide agencies with a flexible system that delivers critical functionality for the signaling and train control architecture the agency selects.

A CBTC design helps the agency achieve moving block separation and improved headways with cab signaling and Automatic Train Operation (ATO). In an ATP design, fixed block separation with signal protection is sufficient. With the design and scope of the RPS now clearly defined, its role in supporting the vital functions required in both design options can be more thoroughly explained.

The goal here is to move out of the more abstract realm of system design to address critical functional requirements for which the agency must be in strict compliance.

RPS IN CBTC

In a CBTC system design, Piper's RPS replaces the traditional combination of roadbed transponders, undercarriage TIAs, and wheel odometry. Optionally, an additional sensor such as LiDAR or Inertial Measurement Unit (IMU) can be used to provide dead reckoning in degraded mode, while a radar or LiDAR device can be included to provide additional train-at-halt determination. This configuration provides immediate cost saving to the agency and improves ease of installation as follows:

- **Carborne -** RPS offers the simplest possible interface with the train - requiring only a bracket and power. This improves carborne maintainability and reduces vehicle weight by moving positioning equipment from the undercarriage to the accessible cab. And because shop space for installation and maintenance is both costly and difficult to secure for a large retrofit, having the ability to perform these tasks in the yard reduces cost and accelerates commissioning.
- **Wayside -** RPS anchors are installed in accessible areas on the wayside rather than in the roadbed. This reduces the risk of critical position equipment being moved during track maintenance and allows workers to reach the units on the wayside under flagging as opposed to scheduling disruptive track outages.

Operational Benefits

- The RPS design in CBTC ensures that a train that de-localizes in the territory, as may occur from a power outage or other CBTC failure, can re-localize instantaneously without the need to slow roll over multiple transponders. This dramatically improves system response time to failures while reducing delays for riders.
- Positional certainty of trains is continuous as opposed to the brief moments when the train rolls over a transponder.
- Work trains are difficult to equip with CBTC, primarily due to physical constraints of putting / powering CBTC equipment on a work train. Installing portable ad-hoc RPS equipment on the vehicles enables them to report their position back to the CBTC Zone Controller (ZC) through the CBTC radio network - or other available network such as LTE or 5G. This data can be integrated with the Automatic Train Supervision (ATS) subsystem to efficiently route revenue trains around work trains to minimize system disruptions.
- In many CBTC designs, agencies are forced to retain trip stops as well as the home and approach signals in order to accommodate mixed fleet operations (e.g. non-CBTC equipped work trains operating in CBTC territory). With the RPS installed, agencies can take full advantage of the efficiencies of CBTC and eliminate this wayside infrastructure from the system.
- The RPS modernizes CBTC and lays the foundation for future improvements. It resets the technological baseline and provides the path for future upgrades and functionality.

Safety Certification

The RPS received its CENELEC SIL-4 certified for position and speed from Independent Safety Assessor (ISA) TUV SUD. As part of a CBTC design, this certification assists the CBTC supplier in achieving the overall system safety targets. Typically, these targets are established by the agency and the General Engineering Contractor (GEC) and quantified as the Mean Time Between Hazardous Events (MBTHE). Piper's RPS rating for Mean Time Between Failure (MBTF) is significant and will help agencies meet their safety objectives and accelerate the CBTC certification process.

Applicable Standards

Piper's RPS has achieved functional safety certification to a SIL-4 level for the following standards:

- EN 50126 Railway Applications: The Specification and Demonstration of Reliability, Availability, Maintainability & Safety (RAMS) v.2017
- EN 50128 Railway applications - Communications, Signaling and Processing Systems – Software for railway control and protection systems v.2011
- EN 50129 Railway applications - Communications, Signaling and Processing Systems – Hardware for railway control and protection systems v.2018
- EN 50159 Railway Applications - Communications, Signaling and Processing Systems – Safety Related Electronic System for Signaling, February 2003, 2010
- EN 50155 Railway applications - Electronic Equipment Used on Rolling Stock v.2017

Piper also meets the following standards for EMI/EMC/Environmental compatibility:

- EN 50121-1 - Electromagnetic compatibility
- EN 50121-3 - Rolling Stock - Train And Complete Vehicle
- EN 50121-4 - Emission And Immunity Of The Signaling And Telecommunications Apparatus
- EN 50155 - Electronic Equipment Used on Rolling Stock
- IEC 60068-2 - Environmental Testing of Electronic Equipment
- AREMA C&S 11.5.1 (Class B)

RPS IN ATP OVERLAY

The Piper RPS is capable of helping agencies achieve their modernization goals without incurring the cost or disruption involved in the commissioning of CBTC. Doing so requires implementing a system that can be added to existing infrastructure to improve overall safety and reliability. We refer to this as the ATP Overlay (ATP-O) approach because it assumes retention of a signaling system in order to meet the IEEE functional ATP requirements of CBTC at a reduced cost and with minimal disruption.

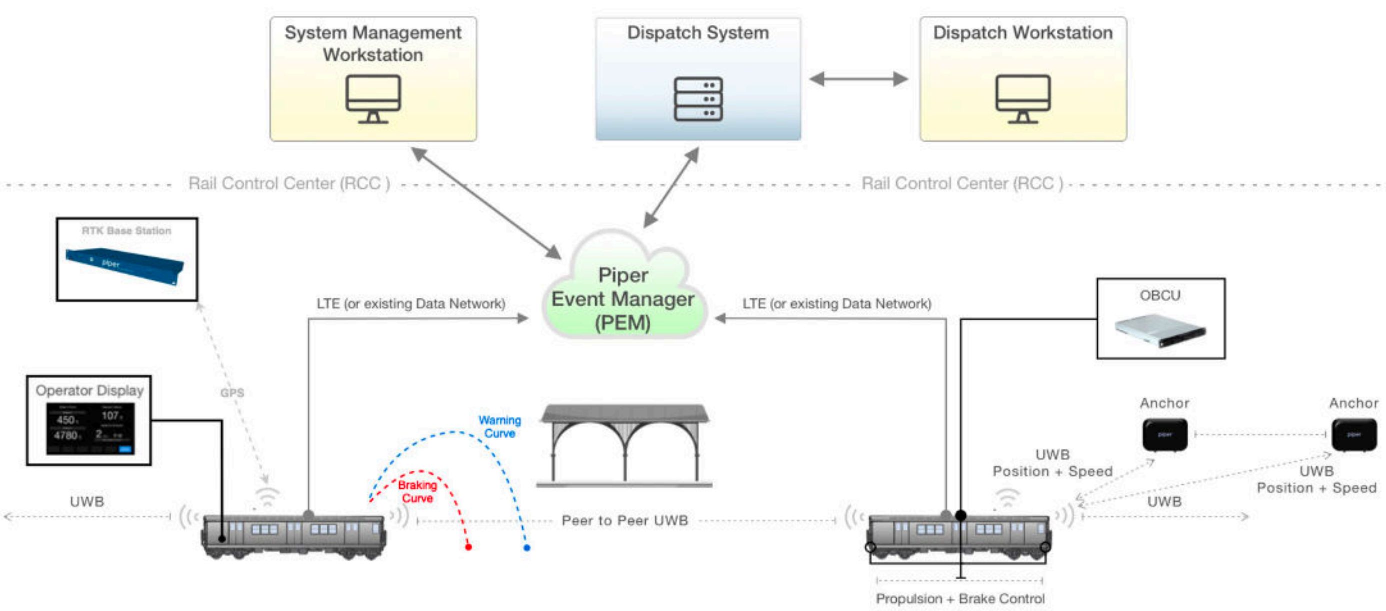
At a high level, ATP-O is a design approach that uses Piper's RPS system identically as it's deployed for CBTC for vital position and speed. But it's expanded to include integrations with existing critical signaling equipment and with the addition of Piper's carborne Safety PLC to initiate braking when an operator ignores one or more protection rules. The result is a comprehensive and convenient system that is competitive with the benefits of full CBTC.

Integration with Wayside Equipment

With ATP-O, agencies can benefit from the ability of trains to communicate directly with wayside equipment while operating in the territory. In addition to determining vital speed and positioning information, Piper is capable of integrating UWB radios into various wayside devices and including the data in critical train control calculations while also displaying the information to the operators. Among the examples for this type of integration are:

- Solid State Interlocking (SSI) - to receive and process switch position to determine safe operation.
- Signal Heads - to determine and display signal aspect to the operator.
- Grade Crossing Controllers - to improve the reliability of train detection near grade crossings.

While Piper has not yet safety certified these types of wayside integrations, use of our SIL-4 radios will accelerate the process with our Independent Safety Assessor to ensure that these integrations meet the requirements for system vitality, or they can be implemented in as a non-vital application similar to PTC. Additionally, this process is certain to consume a fraction of the time required for the more comprehensive CBTC safety certification.



USE CASES

An effective way to illustrate this approach is to return to the IEEE 1474.1 Standards for Communications-Based Train Control Performance and Functional Requirements and describe how ATO-O can deliver on all of them without implementing CBTC. For reference, the following descriptions are all based on the assumption that a DCS is available in the territory as part of the system design.

Train Location / Train Speed Determination

- The Piper RPS is independently SIL-4 certified for position and speed.

Safe Train Separation

- In a CBTC system, this is managed by the ZC. In ATP-O, this is managed by the vital signal system. The RPS, based on its onboard database of the territory, ensures that the train is aware of its position at all times and, based on the speed and braking/warning curve, can initiate a braking action prior to a signal being breached. This is a significant safety improvement over traditional signaling systems.

Overspeed Protection and Brake Assurance

- The RPS is vital speed determination. It can be integrated with Piper's Safety PLC to provide graduated speed control or emergency braking (EB) to enforce overspeeds.

Rollback Protection

- Rollback is a challenge for CBTC as its traditional transponder-based positioning systems have difficulty with slow speed detection. The accuracy of the RPS is a critical enhancement for platform berthing and rollback hazard because it can detect small fluctuations in train movement. In ATP-O these same principles apply and are enforced by the Piper Safety PLC.

End-of-Track Protection

- The RPS provides positioning throughout the territory, including track limits. Protection for this function is similar to that for red signals. Related to this topic, the RPS can also assist with asset management (identifying the location of a train / car) within a congested depot / yard.

Parted Consist Protection / Coupling & Decoupling

- The dual-ended ranging design of the RPS provides positioning data from the front and the rear of the train simultaneously. This data can be used to measure the train consist length and trigger braking action from both units (A1/A2) in the event of a decoupling.

Zero Speed Detection

- The continuous positional certainty of the RPS ensures that it can detect zero speed low speed in critical scenarios such as platform berthing. As mentioned previously, the RPS can be augmented with additional sensors, in this case a radar unit as a secondary zero speed detection system.

Door Opening Control Protection Interlocks

- This is an optional feature of IEEE 1474.1 ATP Functions if the train is being operated by a train crew. The RPS does not directly provide door controls, however, it can be integrated with third party door controllers to ensure zero speed, proper door alignment, and verifying which side of the train is facing the platform prior to activating doors.

Departure Interlocks

- Similar to above, this is an optional requirement of ATP systems if the train is operated by a train crew. If desired, Piper can integrate the ATP-O system with third party door controllers to ensure all doors are properly locked prior to allowing the train to proceed on its route.

Emergency Braking

- RPS integration with the Piper Safety PLC provides emergency braking functionality that can be activated in response to breach of several protection rules.
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Route Interlocking

- This functional requirement ensures that routes through an interlocking be "locked" by the system to prevent multiple routes through an interlocking. As the ATP-O system is overlaid on top of the vital signal system, it is anticipated that the signal system's vital logic would prevent multiple or conflicting positive aspects into an interlocking - leaving the ATP-O system will enforce the signal rules. Alternatively, the ATP-O can also provide feedback to an SSI with respect to movement authority requests coming from the back office.

Traffic Direction Reversal Interlocks

Because trains operate bi-directionally, ATP-O provides traffic direction reversal protection where reversal of traffic direction within a section of track shall not be possible unless:

- All trains within that section of track are at zero speed and constrained against motion in the original traffic direction, and
- The movement authorities for all trains outside of that section of track do not extend into the section and are constrained from being extended into the section in the original traffic direction.

Work Zone Protection

- The RPS database is able to receive updates with dynamic information related to safe operation such as Temporary Speed Restrictions (TSR) and Work Zones. Because the RPS has the full track database loaded in the Onboard Controller it can alert operators to the presence of a work zone and protect it with braking action as described previously in the event that work zone is breached.

Broken Rail Detection

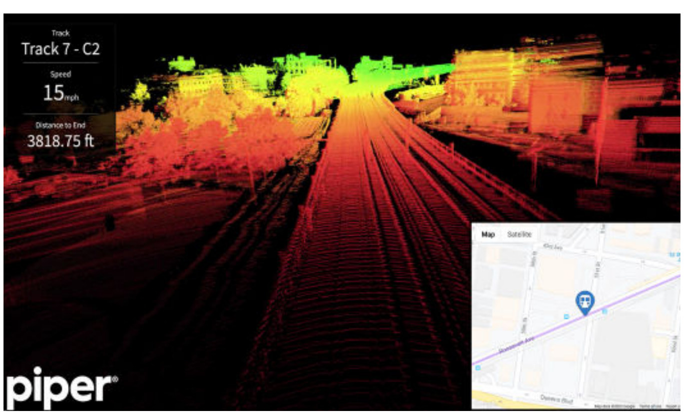
- In an ATP-O design, the signals detect the broken rail. The RPS in turn protects the signals to ensure that a train does not enter a block where broken rail has been detected.

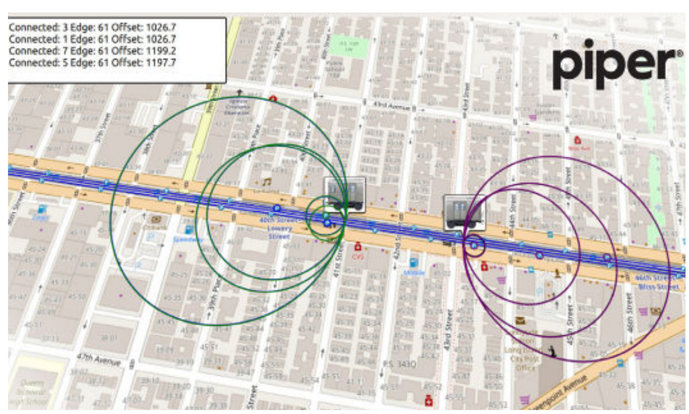
CASE STUDY - AMTRAK

LIMITS COMPLIANCE AND COLLISION AVOIDANCE SYSTEM

Piper is currently deploying a version of ATP-O for Amtrak, specifically on Maintenance of Way (MOW) vehicles.

The system provides limits compliance, collision avoidance, collision detection, and obstacle detection. Vehicle installations have begun and the program is scheduled for full operation across the Northeast Corridor (NEC) in early 2023. While this system doesn’t integrate with a higher level control apparatus like CBTC, it uses track databases and integrations with both vehicles and wayside infrastructure to create a safe environment for MOW vehicles to operate in both travel and work modes. Piper is retrofitting over 700-railbound MoW vehicles and integrating Piper’s back office system into Amtrak's Computer Aided Dispatching system, AMTEC. The program includes the design, development of maintenance manuals, execution of a training program, and furnishing / installation of all equipment on Amtrak’s infrastructure.





UPGRADE & INTEGRATION

Upgrade Path

Mitigation of obsolescence should be top of mind for agencies as they pursue their modernization plans. The RPS provides ongoing obsolescence protection on two levels. First, the system design is based upon components that can be readily sourced through distribution. There are no proprietary, black box components involved and the design and the equipment MTBF is exceptionally long compared with other industry safety ratings. Additionally, because the ATP-O system design uses the same UWB radio configuration as the CBTC design, agencies have the flexibility to upgrade to CBTC at any time, seamlessly, requiring no reinstallation or commissioning of the positioning infrastructure.

Integration with Suppliers

The advent of new and safety certifiable technologies are beginning to have an impact on the product offerings from major train control and signaling suppliers. For the first time, product designs that include “sensor fusion” or “multi-sensor arrays” are being promoted. Piper believes that by using the RPS as a foundation for vital speed and position, agencies can motivate suppliers to provide lightweight, lower cost versions of established industry train control products.

Incremental Upgrade

As stated previously, Transport for London often refers to the implementation of CBTC as a “big bang” undertaking. The process of removing old track circuits, installing zone controllers and new interlocking, as well as retrofitting rolling stock is daunting. Indeed, TfL pressed the industry to come up with an incremental approach because the current state of their lines and the need to keep lines operational would not accommodate a big bang approach. Moreover, the cost of dual-equipping both existing and new rolling stock with train control equipment to be compatible with both the existing track circuits and new CBTC equipment can be cost prohibitive.

In response to these concerns, which are likely to be shared by agencies, Piper has developed an incremental upgrade plan that: minimizes rider disruption, avoids dual-equipping trains, and reduces costs associated with system modernization.

The following points summarize at a very high level the plan and rollout strategy:

- Piper integrates UWB radios with the physical and logical interfaces of existing wayside equipment - specifically, aging signals, switches, and interlocking equipment. This is done primarily so that while the upgrades to CBTC or ATP-O are taking place, both older trains and new rolling stock can operate on the existing track circuits. For the new trains, Piper's onboard controller is updated with software that can receive track codes in real time from the end-of-life system and use it to protect the train according to the ATP functions described above, or pass it through to the CBTC OBCU which had been augmented to temporarily operate based on track code information. Because this information is vital to safe operation, Piper must safety-certify these integrations as a first step in the incremental upgrade plan. But because these integrations use the same radios as Piper's RPS, much of the safety certification has already been accomplished.
- With this wayside equipment integration complete, installation of the RPS wayside equipment can commence. If the line is slated for CBTC, the supplier can begin installation of the zone controllers, AWS equipment, and begin configuring new rolling stock. There is no need to retrofit older rolling stock because the existing track circuits will remain as long as there are legacy trains operating in the territory.
- When the CBTC infrastructure build out is complete, and all new trains have been delivered, the operator can cut over to full CBTC. Removal of the legacy equipment can begin and proceed at a pace that accommodates the agency's operational commitments.

Piper believes that the approach we have defined in this document will help agencies reduce costs in the short term while reducing risks of obsolescence for years to come. We welcome the opportunity to schedule a follow up meeting to discuss the details and answer questions from both the agency and their GEC.

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