Engineering Service for the Signal System State of Good Repair

RTD LRT Signal System Upgrade Options

RTD Contract No. 69076

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Executive Summary

Regional Transportation District – Denver (RTD) has commissioned HNTB to study its Light Rail Transit (LRT) signal system to evaluate the current signaling technology alternatives to upgrade and improve the safety and efficiency of the LRT transit operations. This study focuses on LRT critical elements system improvement options, including civil speed and red signal compliance, enhanced roadway worker protection, and improving system throughput. Some of the factors that prompted this study are lack of automatic speed enforcement capability on the current system and bringing state-of-the-art train control technologies to RTD's LRT. Focusing on upgrading the aging signal equipment is critical to increase the reliability and safety of the LRT operations while becoming Signaling Safety Overlays (SSO) ready for future interfaces.

The key findings of this study captured various elements for consideration. As highlighted by case study descriptions, the SSO alternatives mentioned herein have been tested and proven on North American transit systems and can be readily applied to RTD LRT operations. All three SSO technology alternatives can ensure proper train speed compared to the current LRT operating system. New signal design technology can improve transit headways by removing the need for a double red signal layout, or overlap block, used in the existing Automatic Block Signal (ABS). Another improvement can be the Communications Based Train Control (CBTC) technology that offers moving block technology, providing all required SSO functions and improving system headways. Another element for potential improvement is integrating the Ultra-Wideband (UWB) train positioning technology. Because of the nature of the intense operation on the RTD LRT, the roughly estimated duration of the SSO implementation is about eight years to apply any of these technologies to the current systems and RTD will need to retrofit its fleet with propulsion and braking system interfaces, onboard control equipment, and operator display/control units (CDU). Rough estimates for a capital cost of an improved SSO differ by technologies costing between $91M for the Cab Signal SSO, $198M for Balise based SSO, $185M for CBTC SSO, and CBTC Moving Block at $224M.

Critical next steps in implementing a new SSO on the RTD LRT system include addressing RTD's LRT train control state of good repair (SOGR) issues, finalizing the technology selection, and performing an in-depth study on application and return on investment. Progress on LRT SSO system specifications and conceptual designs will depend on the client's instructions but be achievable with the initial in-depth study.

The table below summarizes the technologies analyzed in this study and their key operational and implemental features.

Summary of Alternative SSO/CBTC Technologies				
Features, Complexity, Cost	Technologies			
	Cab Signal SSO	Balise SSO	CBTC SSO	CBTC Moving Block
Civil Speed Enforcement, Signaled Territory	YES	YES	YES	YES
Civil Speed Enforcement, Non-Signaled Territory	NO	YES	YES	YES
Roadway Worker Protection	YES	YES	YES	YES
Increase Throughput of System	Neutral	Neutral	Neutral	YES
Data Radio System	NO	Optional	YES	YES
Wayside Installations	Moderate	Complex	Least Complex	Least Complex
On-board installations	Moderate	Complex	Complex	Complex
Central Control / Back Office	Least Complex	Moderate	Complex	Complex
Implementation Cost	Least Expensive	2nd most Expensive	3rd most Expensive	Most Expensive
Diversity of Suppliers	Single	Multiple	Single	Multiple

OTHER CONSIDERATIONS

LRT Highway-Rail Grade Crossing Warning Systems

Highway-rail grade crossing collisions are a primary concern for railway authorities and the public at large. The main function of the highway-rail grade crossing warning systems is to provide warnings to road users, including automobiles, bicycles, and pedestrians, of the crash-imminent situation at the grade crossing locations. The safety cases of the systems are usually treated independently from the train operation safety as mentioned in the body of this study. As such, the existing LRT highway-rail grade crossing warning systems, including the interfaces to traffic systems, are marked as “no change” in this study. If the Authority desires, a separate safety improvement study to the existing LRT highway-rail grade crossing warning systems may be conducted.

SSO Data Radio Communication System and Licensing

The Federal Communications Commission (FCC) is responsible for managing and licensing the electromagnetic spectrum for commercial users and for non-commercial

users including state, county, and local governments. This includes public safety, commercial and non-commercial fixed and mobile wireless services, broadcast television and radio, satellite, and other services. LRT Data Radio Communication System Licensing, if needed for the selected SSO technology, will be part of the Contractor's responsibility during system implementations. The selection of the type of new data radio communication system shall ensure that both the equipment and licensing will support the lifetime of the selected SSO system.

State of Good Repair of LRT Communication Systems

Any selected SSO will rely on a State of Good Repair of an existing LRT Communication System. Communications networks include systems and sub-systems that operate in layers. The primary system, the Communications Transmission System (CTS) is the backbone of the network which carries the data created by various sub-systems – security cameras, message signs, fare collection devices, train control systems, etc. The CTS includes physical layer components (optical fiber and copper cabling) and network elements (routers and switches) that provide "any to any" connectivity to the sub-systems. This CTS backbone can also include wireless technologies in sub-systems that communicate with moving targets (trains and buses). This combination of systems and sub-systems must be integrated such that it forms a seamless infrastructure that supports a variety of operations and business requirements. The costs (and risks) associated with the communications network infrastructure include network maintenance, operations and test, and documentation. Network maintenance costs include: network cable management and fiber "hygiene," network element component maintenance and repair, UPS battery management, and radio frequency/wireless (FCC) licensing and/or spectrum leases. Risks associated with network maintenance include vendor end-of-life and network element/cable aging, spectrum interference management, and environmental deterioration. Operations and testing costs and risks include the hugely important area of cybersecurity and malware protection, failure simulation and recovery, power checks, network availability assurance, and retaining skilled labor to operate the network. Risks include network element interoperability between vendors, and new technology integration. Documentation costs and risks include data and firmware backups, configuration and profile management and archiving, resource/supply-chain forecasting, contingency planning and as-built updates. Maintaining a State of Good Repair of the communications infrastructure will address all of the above areas. If the Authority desires, a separate State of Good Repair study to the LRT Communications systems may be conducted.

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Acronyms and Abbreviations

Acronym	Definition
ABS	Automatic Block Signals System
ACSES	Advanced Civil Speed Enforcement System
AFO	Audio Frequency Overlay
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Stop, Automatic Train Supervision
BCM	Base Communication Manager
BOS	Back Office Server
BRCM	Base Radio Control Module
CBTC	Communication-Based Train Control
CCS	Central Control System
CP	Control Point
CR	Commuter Rail
CSS	Cab Signal System
CTC	Centralized Traffic Control
CTS	Communication Transmission System
E-ATC	Enhanced Automatic Train Control
EIC	Employee-In-Charge
ETCS	European Train Control System
GETS	GE Transportation Systems
HMI	Human-Machine Interface
I-ETMS	Interoperable Electronic Train Management System
ITC	Intermittent Train Control
ITCM	Interoperable Train Control Messaging
ITCS	Incremental Train Control System
LEU	Lineside Electronic/Encoder Unit
LRT	Light Rail Transit
LRV	Light Rail Vehicle
MCM	Mobile Communications Manager
MD	Mandatory Directives
NEC	Northeast Corridor
NGPS	Next Generation Position System
OCM	Office Communications Manager

Acronym	Definition
PRT	Portable Remote Terminal
PSR	Permanent Speed Restrictions
PTC	Positive Train Control
PTS	Positive Train Stop
RTD	Regional Transpiration District
SSO	Signaling Safety Overlay
TCP/IP	Transmission Control Protocol and the Internet Protocol
TMC	Train Management Computer
TSR	Temporary Speed Restrictions
UWB	Ultra-Wide Band
VHLC	Vital Harmon Logic Controller
WCM	Wayside Communication Manager
WIU	Wayside Interface Unit
WSRS	Wayside Status Relay Service

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Introduction

To fully appreciate the state-of-the-art systems discussed herein, the Signaling Safety Overlay (SSO) system term is used to describe the recommended options that will provide the functions to prevent train-to-train collisions (red signal compliance) reliably, movement through the mainline switch in the improper position (red signal compliance at interlockings), over-speed, incursions into an established work zone, as well as improving transit throughput.

While this paper provides insight into state-of-the-art technologies, it is essential to note that these train control technologies are constantly evolving. The system overviews offered in this paper may not include the latest generation of the equipment. With that being said, this paper is intended to provide a basic understanding of how an SSO system should be implemented and the necessity of managing the technology change.

While implementing any SSO, it is vital to allow adequate time for the program to develop, especially during the project's engineering phase, ensuring that all stakeholders have input. Moreover, any project of this magnitude should have a dedicated support team from the Agency, including all the stakeholder departments, such as Signals, Communications, Vehicles, Operations, Safety, and Training. The personnel assigned from each department should be enthusiastic about the new technology as it will be necessary for them to learn the technology to provide total value. They will become the system experts.

Subsequently, any systems integration program is not likely to go flawlessly. There will always be some changes as the stakeholders become more involved in the technology. Furthermore, it should be anticipated that some component changes will occur as the system is tested and validated, so expect some system modifications. Finally, the Agency needs to be actively engaged with the Contractor in determining the content of the training material. The training must be made sustainable so that new personnel can be trained as needed, as this is a critical component for the new system integration.

Existing LRT Systems Overview

The RTD LRT system consists of about 60 route miles of primarily double tracks, including:

- CC - Central Corridor, 5.3 miles, Broadway station to 30th & Downing station, opened 1994

- SW - Southwest Corridor, 8.7 miles, Broadway Station to Mineral Station, opened 2000
- CPV - Central Platte Valley Corridor, 1.8 miles, Auraria West Station to Union station, opened 2002
- SE - Southeast Corridor, 15 miles, Broadway Station to Lincoln Station, opened 2006
- SERE - Southeast Rail Extension, 2.3 miles, Lincoln Station to Ridge Gate Pkwy Station, opened 2019
- WC - West Corridor, 12.1 mile, CPV junction to Jefferson County Gov Center station, opened 2013
- PR - Parker Road Corridor, 4 miles, Southmoor Station to Nine Mile Station, opened 2006
- I225 - I225 Corridor, 10.5 miles, Nine Mile Station to Peoria Station, opened in 2017

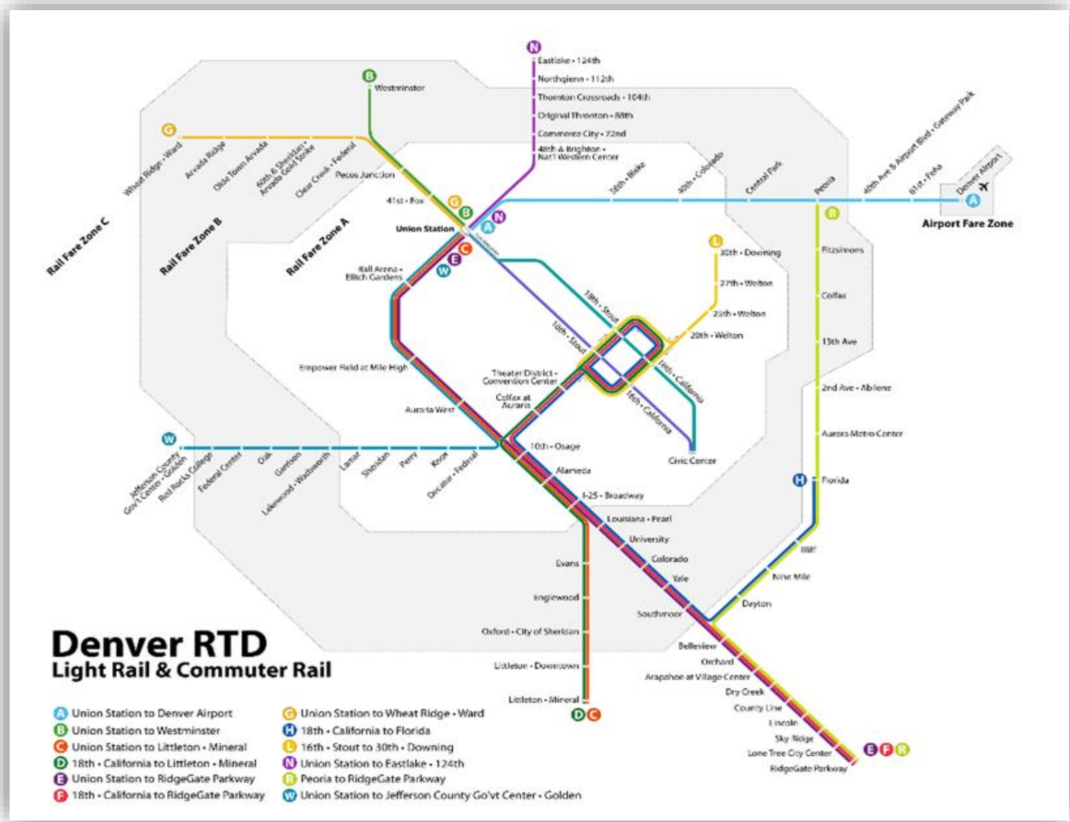

Figure 1 - Map of Denver RTD Light Rail & Commuter Rail

LRT Signal Systems

Wayside signaling: Automatic Block Signals System (ABS) with color light signals for normal direction traffic. Double red signals or overlap circuits are used to protect red signal overrun.

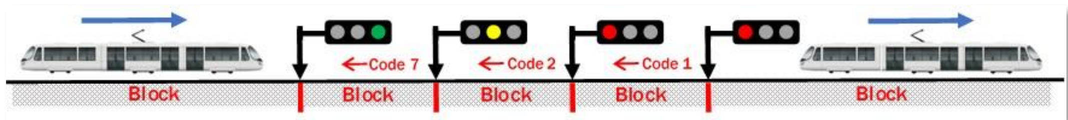

Figure 2 - ABS. Track Codes Transmission to Control Color Light Signals

Onboard signaling: Cab codes (go/no-go) transmitted on the track are detected by pick-up antennae on the train. The onboard Automatic Train Stop (ATS) will stop a train if it passes a red signal. Cab codes used: CAB270 or CAB180 - ATS mode, CAB75 – NON-ATS mode, CAB0 - train automatically stops.

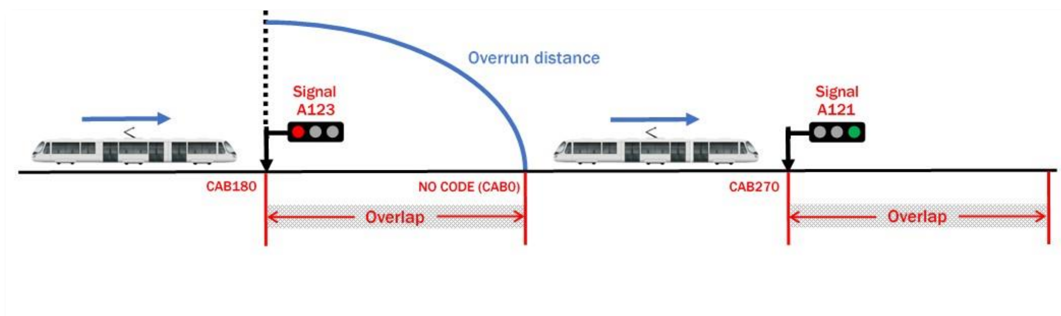

Figure 3 - ABS. Red Signal Overrun Protection

- Interlocking relay houses contains either Harmon VHLC or GETS ElectrologIXS signals processor
- Intermediate signal relay houses contain GETS EC5 signals processor at most locations
- Crossing relay houses contain either Harmon VHLC or GETS ElectrologIXS signal processors or relay circuits. Some crossing relay houses are combined with intermediate signal relay houses or interlocking relay houses
- Solid-state electronic coded track circuits in mainline tracks between interlockings
- Power frequency track circuits in interlocking
- Audio-frequency overlay track circuits for overlap circuits, signal overrun detection, and highway grade-crossing warning approach circuits
- Mixed traffic section in the non-ABS territory, with operators following traffic-type signals: In the Central Corridor the northbound ABS signal territory ends at the south of

Colfax/Auraria Station, the downtown Denver non-ABS segment is about 2.3 miles. In I-225 Corridor, the 1.5 miles tracks between Ellsworth Interlocking and south of Aurora City Center Station is a non-ABS territory, and

- The LRV operator operates according to the wayside signals, speed restriction signage displayed, and conventional operating rules.

The list of relay houses and types of equipment is included in the Appendix of this report.

Light Rail Vehicles

- Model SD-100 and SD-160 manufactured by Siemens Mobilities
- A total of 201 LRVs are in service
- Vehicles have operator compartments at both ends, allowing them to reverse direction at terminals without loop tracks, and
- LRV's are equipped with GETS UltraCab II Cab Signal system and ATS system.

LRT Communications System

- Central Control System (CCS) provides supervisory control to signal systems, and
- Communication Transmission System (CTS) provides copper and fiber optic cables to communicate between signal relay houses and CCS.

HNTB

Alternative SSO/CBTC Technologies

Alternative Technologies Evaluations and Implementation Analysis

There are two standard SSO methods currently being used in railroad signaling. The first uses fixed signaling infrastructure such as track circuits and wireless Balise (AKA transponders) to communicate with the onboard speed control unit. The other uses wireless data radios spread out along the rail line to transmit dynamic information. The wireless data radio implementation allows the train to send its location to the signaling system, enabling moving or "virtual" blocks. The wireless implementation is generally cheaper in terms of equipment costs but is less reliable than using "harder" communications channels.

Included detailed examples:

- Cab Signal SSO technology: A SSO system that uses an E-ATC cab signal system (CSS)
- Balise based SSO technology: A SSO system that uses Balise wayside-to-train communication devices
- Communication-Based Train Control (CBTC) SSO: An SSO system using CBTC
- CBTC moving block: A CBTC system that provides moving block technology with full SSO functions
- Ultra-Wide Band (UWB) train positioning: a next-generation train positioning technology that can be fully integrated with CBTC or augment GPS-based signaling systems. Due to its short service record, there is no current safety case for UWB on train control. The UWB is listed for reference but is not included in SSO technology evaluations
- Satellite-based SSO: A Satellite-based signaling system can be configured as a standalone or overlay SSO system. Also, due to the lack of examples in urban rail application, this technology is listed for reference but is not included in SSO technology evaluations

A summary description of each of the alternative technologies is listed in Table 1 - Alternative SSO/CBTC Technologies Descriptions. The pros and cons of each alternative technology are listed in Table 2 - Pros and Cons of Alternative Technologies below.

Technology	Description
E-ATC Cab Signal SSO	Wayside cab speed code generator transmits speed code in accordance to track speed limit and signal status ahead. Cab speed codes contained in the track circuits are sent to the train. The permitted speed is checked against the actual speed and, if the allowable speed is exceeded, a brake application is initiated.
Balise-based SSO	Fixed data Balise are passive elements and transmit only fixed telegrams which tell the passing trains their current position in the network and track speed limit ahead. Dynamic data Balise is connected to a signal via a lineside electronic unit (LEU) and transmits the movement authority according to the current signal aspect. The onboard processor produces a speed profile and enforces the speed limit if the actual speed is higher than the profile speed.
CBTC SSO	Trains use GPS and an onboard odometer to determine their position, and track Balise may also be used as a positioning device. Radio communications transmit wayside signal status, as well as OCC directives to the train. The Radio also transmits train positions to OCC. Civil speed limits are stored in the onboard processor database. The onboard processor produces a speed profile and enforces the speed if the actual speed is higher than the profile.
CBTC Moving Block	Trains use GPS and onboard tachometer to determine their position, and track Balise may also be used as a positioning device. Radio communications transmit the location of other trains, as well as OCC directives to train. Radio also transmits train positions to OCC and other trains. civil speed limits are stored in the onboard processor database. The onboard processor produces a speed profile and enforces the speed if the actual speed is higher than the profile.
Satellite-based SSO	Trains use GPS and an onboard odometer to determine their position. Wayside equipment provides the status of track switches, track circuits, and signals to train via radio. Train signal enforcement is according to the rulebook. Train enforces civil speed limits from the database.
Ultra-Wide Band (UWB) Train Positioning	UWB is a radio frequency technology that uses a considerable bandwidth to transmit and receive small pulses to calculate precise train locations. A UWB system utilizes UWB transponders located along the wayside and onboard the train. Onboard equipment will determine the maximum allowable speed based on approach distance to the civil speed limit or a signal with a restricting aspect, warn the operator and, if necessary, apply the brakes.

Table 1 - Alternative SSO/CBTC Technologies Descriptions

Technology	Pros	Cons
E-ATC Cab Signal SSO	Relatively simple to upgrade. No new wayside device or new radio system is needed.	It cannot be used in non-signaled territory for speed limit enforcement. Requires cab signal control line redesign. SSO may slow down train operation and may have a negative impact on system throughput.
Balise-based SSO	It can be used in the non-signalized area for speed limit enforcement.	Technology is new to RTD LRT. Require new onboard equipment and

Technology	Pros	Cons
	Does not require continuous radio coverage.	a more complicated interface to the vehicle. SSO may slow down train operation and may have a negative impact on system throughput.
CBTC SSO	RTD Commuter rail has a similar system installed.	Technology is new to RTD LRT. Require a new radio system covering the entire corridors. Implementation is likely to be complex and time-consuming. SSO may slow down train operation and may have a negative impact on system throughput.
CBTC moving block	Can reduce headway and improve system throughput	Technology is new to RTD LRT. Require a new radio system covering the entire corridors. Implementation is likely to be complex and time-consuming.

Table 2 - Pros and Cons of Alternative Technologies

E-ATC Cab Signal SSO Technology

At the trackside, the signal aspects of the sections ahead are monitored and passed to the relay house code generator for each block. The code generator sends the appropriate codes to the track circuit. Cab signal ATP speed codes contained in the track circuits are transmitted to the train. The track speed limit determines the maximum allowable speed on the block. Cab speed codes are detected by pick-up antennae mounted on the leading end of the train under the driving cab. This data is passed to an onboard decoding and safety processor. The permitted speed is checked against the actual speed and, if the allowable speed is exceeded, a brake application is initiated. The data is also sent to a display in the cab, allowing the train operator to respond and drive the train within the permitted speed range.

Case Study: E-ATC by Alstom

The Enhanced Automatic Train Control (E-ATC) System is based on cab signaling with color-light wayside signals. Electro-Code track circuits between interlockings provide train detection as well as convey signal aspect information between locations. Cab Speed code is inserted to track circuits and transmitted to train. Within interlockings, DC or AC track circuits are used for train detection.

The onboard component of the train control system is installed on rail cars operating on the rail corridor. The E-ATC System protects against train-to-train collisions, switch protection, and enforcement of zero speed before reaching a stop signal. The E-ATC

System's foundation uses service-proven track circuits, supplemented by a vital wayside signal system and onboard logic. The system includes functionality to enforce all permanent speed restrictions (PSR), temporary speed restrictions (TSR), and mandatory directives (MD), as well as Centralized Traffic Control (CTC) inputs to the vital wayside signal system for TSR and MD enforcement, including roadway worker and grade crossing malfunction protection.

The E-ATC wayside signal system and onboard components are designed and built on well-defined and proven fail-safe principles. The vital wayside logic prevents any human error by the dispatcher or CTC server from moving the switch position or clearing a specific route unsafely.

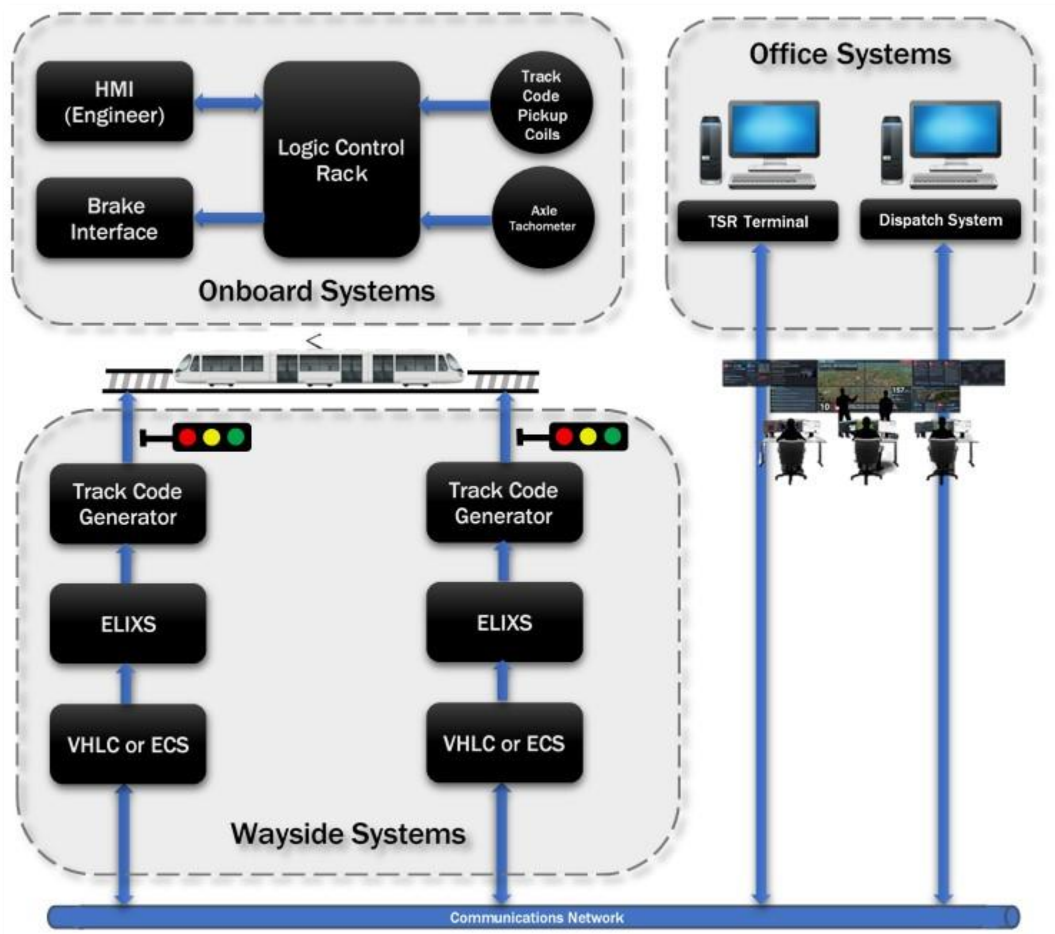

Figure 4 - E-ATC Architecture - Wayside Segment [1]

E-ATC is a wayside-centric, vital overlay system that operates through wayside speed code transmissions to the vehicle and the onboard segment's assimilation and data processing. The critical onboard element continuously accepts, validates, and

[1] Source: Alstom

processes operating data obtained from onboard peripheral devices and the wayside segment through traditional track codes transmitted via the rails. The data elements are validated and combined in such a way as to eliminate single points of failure at a system level and reduce the overall probability of unsafe failure to an acceptable level. This wayside-centric approach minimizes the effect of communications data errors, data conflicts, data latency, and malicious data communication actions, facilitating safe operation.

The vital signal system provides the core functionality. Each control point (CP) in the wayside segment contains an ElectrologIXS vital controller performing the following tasks:

- Occupancy determination through vital track circuits
- Safe train separation per railroad signaling principles
- Route locking
- Track code generation to cascade speed and signal status between adjacent wayside controllers
- Cab code generation to communicate cab signal information to the onboard controller
- Switch control

The Wayside Segment of the E-ATC System will consist of several components and functions, most currently in use as part of the existing ABS signaling system. Some of which will be added to achieve SSO functionality. The current wayside signal system employs the Vital Harmon Logic Controller (VHLC) or ElectrologIXS for interlockings and the Electrocode (EC) 5 at intermediate signal locations. The existing cab signal generators will be upgraded to provide speed codes such as 0, 15, 25, 35, 45, and 55 mph. The upgraded code generator generates cab signal speed codes. The pre-existing wayside signal system drives light-emitting diode (LED) wayside signals based on occupancy of the train detection circuits and the selected train route. The existing LED wayside signals reflect the appropriate aspect based on track occupancy and train route. The current wayside signal system automatically displays route information through LED wayside signals between control points based on track codes received from adjacent automatic intermediate signals or CPs. Existing EC5 track circuits are implemented between CPs, provide train detection, and convey aspect information between locations. The added E-ATC system provides cab signal speed codes for all track circuits.

Onboard Segment

Vital control of the onboard segment is provided by Ultra Cab II (UCII) equipment, providing the following functionality:

- Train speed determination
- Cab-Code determination
- Aspect display
- Enforcement alerts
- Speed limit enforcement through vital penalty brake application

The onboard segment receives and interprets the cab signal speed codes generated by the wayside segment. The onboard component notifies the train operator that the train's maximum speed can be safely operated and enforces adherence to the associated speed limit.

LRVs are bidirectional and have coils located under each cab end in front of each leading wheel on the A End and B End. The pre-existing coils detect coded cab signals that are transmitted through the rails by the signaling system. The pre-existing Alstom Ultra Cab II (UCII) will be upgraded to decode new speed codes such as 0, 15, 25, 35, 45, and 55 mph. The received speed code will be used to display and enforce the maximum authorized speed associated with a particular block. Speed limits are presented via an onboard display unit. The existing ATS function will be removed. Maximum speed authorities and time-to-penalty are displayed on the display panel. If the operator exceeds the authorized speed, a mandatory full-service stop is enforced by the onboard equipment.

The onboard segment includes an event logging function and reporting system. The onboard data of the vehicle's event recorder is stored in a crash-hardened event recorder. There is no data connection from the onboard to the central control office.

Non-Vitality of Office segment and Communication Segment

The office segment consists of CTC technology. The core system logic and communications processing software is hosted on the servers, while the user interface for dispatchers is presented on the CTC computers.

The office segment provides the following non-vital functionality:

- Timetabling/Scheduling of routes
- Visualization of the track layout, aligned routes, train position, and switch/signaling status
- Application of Temporary Speed Restrictions
- Application of Mandatory Directives

A core concept of E-ATC architecture is that office segment messages to the vital wayside processor are not direct controls but requests. In all cases, the office/CTC system issues a non-vital request transmitted by the communication segment to the wayside. The vital ElectrologIXS controller checks each request before it is implemented. No message from the dispatching system can cause the wayside controller to present an unsafe condition. The wayside segment prevents the issuance of overlapping and inconsistent authorities in a safety-critical manner. If an unsafe request were to be received from the CTC system, then the vital wayside processor will reject the request, fail to comply with the dispatching command, and provide a message to the dispatcher that the request was not implemented.

Communication networks such as fiber optic cables are used to support daily operations. The communications infrastructure provides data services to all wayside locations.

Enforcement of Permanent Speed Restrictions (PSRs)

The wayside segment of the E-ATC system will be configured to communicate the maximum authorized speeds that reflect permanent speed restrictions (PSRs) for the corridor. The wayside segment generates and transmits data via the rail, the applicable cab signal speed code rate, and the onboard computers detect the cab signal code and display the corresponding speed on the engineer's computer display unit.

Enforcement of TSR, WZ, and MD based Speed Reductions

The dispatcher issued temporary speed restrictions (TSR) and mandatory directives (MD) through the office segment and send them to the wayside equipment through the communication segment. The TSR function can be implemented on any contiguous set of track circuits. Dispatchers will use the TSR Function to implement zero speed and non-zero speed TSRs, WZs, and MDs. The vital wayside processor checks each request for validity and whether it can be implemented safely. Once implemented, the wayside equipment sends confirmation back to the dispatcher and vitally enforces and maintains the restriction until the dispatcher removes it. Should a restriction fail to apply, the wayside returns an alert to the dispatcher.

Two actions are required to release a TSR or MD: First, the dispatcher issues the release request. In response, the wayside equipment returns an "acknowledge receipt" message to the dispatcher but does not yet release the restriction. The dispatcher must respond with a second release request. Only upon successful receipt of the second release request will the wayside release the restriction.

A TSR heartbeat is provided to ensure that the wayside segment always has valid and current restriction information. A status message is sent from the office to each wayside control point (CP), and the wayside replies to the office with a status message. If there is a mismatch, an error message will be displayed to the dispatcher.

Balise Based SSO Technology

In the examples of track circuit-based systems, the ATP data from the track to the train is transmitted by using coded track circuits passing through the running rails. It is known as the "continuous" transmission system because data is given to the train all the time. However, it does have its limitations. There are transmission losses over longer blocks, which reduces the effective length of a track circuit to a limit. The equipment is also expensive and vulnerable to bad weather, electronic interference, damage, vandalism, and theft. To overcome some of these drawbacks, a solution using intermittent transmission of data has been introduced. It uses electronic beacons placed at intervals along the track.

In the best-known system, originally developed by Ericsson in Sweden and formerly marketed by Adtranz (now Bombardier), there are usually two beacons, a location beacon to tell the train where it is and a signaling beacon to give the status of the sections ahead. The French word “Balise” is used to distinguish these beacons from other kinds of beacons. Data processing and the other ATP functions are similar to the continuous transmission system.

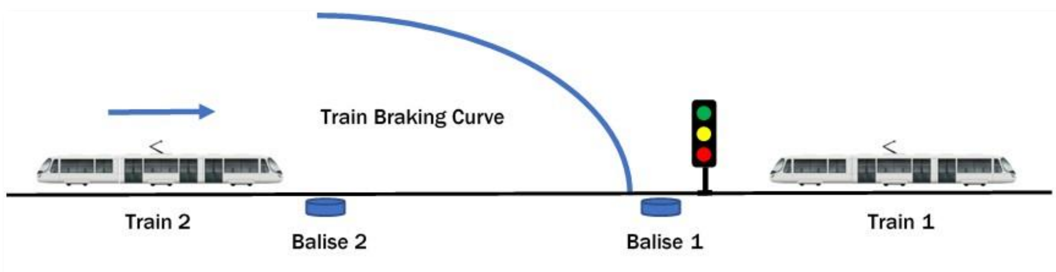

Figure 5 - Balise SSO, Basic Layout Diagram

In Figure 5 (above), the Balise 2 (beacon) for the red signal gives the approaching Train 2 room to stop. Train 2 will get its stopping command on Balise 2 to stop before it reaches the signal. The Balise 1 (beacon) causes an emergency stop if the train attempts to pass while the signal is still in danger.

A disadvantage of the beacon system is that once a train has received a message indicating a reduced speed or stop, it will retain that message until it has passed another beacon or has stopped. This means that if the block ahead is cleared before Train 2 reaches its stopping point and the signal changes to green, the train will still have the stop message and will stop, even though it doesn't have to. In order to avoid the situation of an unnecessary stop, an intermediate beacon may be provided or use an infill loop, as illustrated in Figure 6. This process updates the train as it approaches the stopping point and will revoke the stop command if the signal has cleared. More than one intermediate beacon can be provided if necessary.

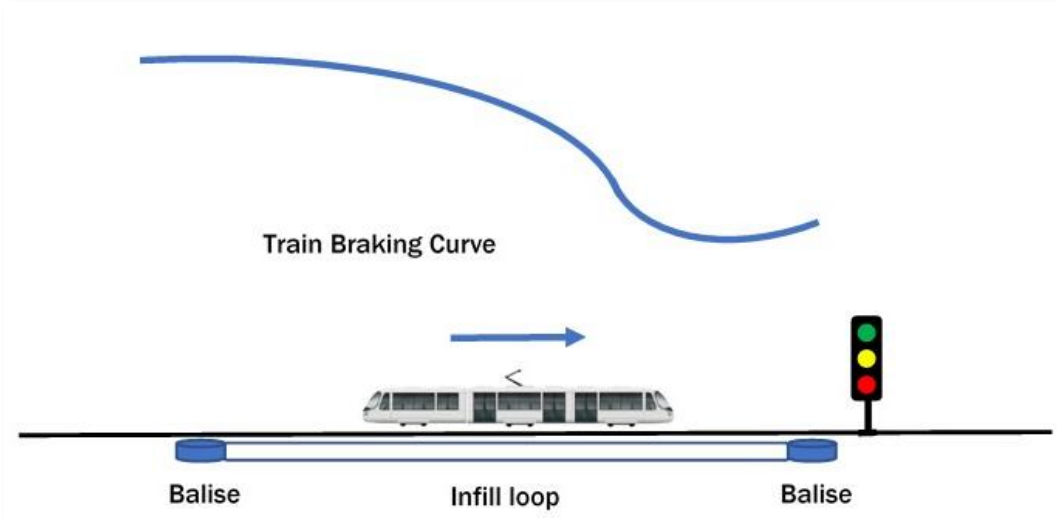

Figure 6 - Balise SSO, Layout with Infill Loop

Case Study: ACSES by Alstom

Advanced Civil Speed Enforcement System (ACSES) provides railway trains with positive enforcement of "civil" speed restrictions (those based on the physical characteristics of the line). The onboard components keep track of a train's position and continuously calculates a maximum safe braking curve for upcoming speed restrictions. If the train exceeds the safe braking curve, then the brakes are automatically applied.

The system enforces two speed restrictions: permanent speed restrictions represent maximum safe speed for track geometry and other conditions. Temporary speed restrictions apply to all other conditions, including track defects, lineside hazards, and maintenance workers in and around the track area.

Data regarding permanent speed restrictions and other information about the permanent way and track configuration is obtained in chunks from the track-mounted transponders and stored in an onboard database. Information regarding temporary speed restrictions is given to the train while en route via a wireless data system. The onboard equipment tracks the train's position by counting wheel rotations between the transponders, serving as fixed location references. A penalty brake application brings the train to a complete stop if a train's crew exceeds a speed restriction.

For a system equipped with a cab signaling system, the cab signal codes are fed into the ACSES cab display unit, which then enforces the more restrictive of the two speeds. The onboard ACSES unit is backward compatible and can function where only the cab signaling is present without the ACSES overlay and situations where

ACSES is available without cab signals.

ACSES also enforces a positive stop at signals displaying an absolute Stop indication. The transponder information allows the train to track when approaching an absolute signal and determine if a positive stop is required depending on cab signal indication and information provided via a local data radio. The system is calibrated to stop the train somewhere within the "Positive Stop Zone." The engineer must engage the Stop-Release button before the brakes can be released to pass the stop signal or otherwise move the train without a more favorable signal indication.

The combination of continuous cab signals (ATC system) and ACSES provides collision protection, enforcement of all speed restrictions, and track possession by maintenance forces.

ACSES II is a similar system by Bombardier/Siemens. ACSES uses cab signaling to provide speed restriction enforcement, whereas ACSES II uses a data radio link to communicate with the train.

The use of ACSES II in Non-Cab Signal/non-ATC territory retains the robust overlay functionality. It applies to an Automatic Block Signal (ABS) or a Controlled Manual Block (CMB) system. In addition, ACSES II in Non-ATC territory provides for an enforced stop at all automatic signal locations displaying their most restrictive indication (Stop and Proceed or Restricting) and all CMB signals indicating a Stop signal aspect. With the absence of an ATC system, the functions of positive train separation and protection against movement through a misaligned switch are provided by the wayside signal system.

Civil Speed Restrictions

Civil speed restrictions are classified into two categories: Permanent Speed Restrictions and Temporary Speed Restrictions.

Permanent civil speed restrictions are those restrictions that are placed into the permanently mounted transponder sets, which include data for both directions of travel and define civil speeds for bridges, curves, hills, interlockings, etc. Permanent speed restrictions do not generally change unless there is a physical change to the tracks.

ACSES can enforce temporary speed restrictions from temporary transponders (those placed by work crews). Three sets of transponders are used for a temporary restriction. The first transponder set is the Advance Warning set. The second is the Start Temporary Restriction set, and the third is the Resume set. When ACSES encounters an Advanced Warning, transponder set the train will immediately start to decelerate so that it will be able to be at the prescribed temporary speed upon arriving at the Start Temporary Restriction set. The Advance Warning set is usually placed at a braking distance from the Start set of the temporary speed restriction. For bi-directional temporary speed restrictions, four transponder sets are required. Temporary speed restrictions supersede any other speed restriction unless a lower speed restriction is received. Upon encountering the Resume set, ACSES returns to the last civil speed enforced for that section of track. TSRs replace temporary wayside sets via data radio in ACSES II.

Onboard equipment

The onboard equipment consists of a computer that stores the route characteristics database, a distance measurement subsystem to track train position, an antenna subsystem for the track-mounted Balise, and a data radio subsystem for communication with wayside systems. The operator has a consolidated display in the cab that displays the train's ACSES target speed, cab signal speed (if applicable), and other useful operating information.

Field equipment

The system begins with passive transponders attached between the tracks electrically powered by an electromagnetic field when a locomotive passes over them. The transponders digitally convey their identification information and other relevant bits of information wirelessly via an onboard antenna, allowing the locomotives to know precisely when they have reached a particular waypoint. This location information is utilized by the onboard systems when consulting its database of speed restrictions and track characteristics to calculate a real-time braking curve.

As the locomotive proceeds down the track, the onboard systems communicate via radio to the region's trackside Base Communications Manager (BCM) data radios. They request any temporary speed restrictions for the next three or more track regions, ensuring that the locomotive's database is continuously updated with any possible temporary restrictions issued by the train dispatcher. Wayside Communications Managers (WCM) link all the BCM’s in the region to a backhaul network which allows them to communicate with the dispatcher's office and associated control systems via TCP/IP. This design provides trains with information about speed restrictions as soon as they go into effect without relying on voice communications with the train crew.

Additional BCM data radios located at interlockings transmit information relating to absolute stop signal indications and any speed restrictions of the train's route through said interlocking. Speed information acquired in this fashion will be displayed on the ACSES speed readout to supplement any speed information provided by the cab signaling system. After a positive stop, the data radios will also transmit information releasing the train from the stop when track conditions permit. Such information about the track occupancy status, switch position, signal indication, and a host of other vital inputs is accumulated by wayside encoders before being sent to the BCMs for transmission to the locomotives.

The ACSES system also supports using temporarily fixed transponders to enforce temporary speed restrictions as an alternative or backup to using the wireless network.

Office equipment

In the office where dispatch and control are performed, a system provides a visual indication of the communications status with all locomotives and a close approximation of where each locomotive is currently located along the track. Suppose maintenance is needed along any section of the track before a work crew is granted authority to proceed. In that case, a temporary speed restriction (TSR) is created in the office computer systems. After a series of verifications and procedures, the TSR is presented to the ACSES office system. When a locomotive issues a query for TSRs for a given region, the WCM conveys the request for information to the office system via TCP/IP. The response is transmitted back to the locomotive, which updates its local database with any restrictions.

Fail-safe operation

Suppose a locomotive cannot automatically retrieve temporary speed restriction information. In that case, permanent speed restrictions will continue to be enforced in a total failure of the onboard ACSES system. The engineer may revert to the use of the cab signal system without civil speed enforcement. Both situations require permission from the train dispatcher and are accompanied by additional maximum speed restrictions.

At interlockings where the BCM data radio is either not installed or not functioning, the train will determine if a positive stop is necessary via the cab signaling system. Suppose it is needed to pass a signal at Stop after receiving authorization from the dispatcher. In that case, ACSES will limit the train to 15 miles per hour within the interlocking limits after using the “Stop-Release” button.

The cab signals are considered a completely independent system that transmits a continuous stream of codes through the rails instead of via wireless transmission. Any fault in the ACSES overlay will not affect the cab signal system, and a cab signal failure will not affect the ACSES system. Without cab signals, ACSES will continue to enforce positive stops at absolute signals. All permanent and temporary speed restrictions, and a positive stop at any signal at the entrance to cab signal without a fixed wayside signal territory that is not displaying "Clear to Next Interlocking."

Case Study: ACSES by Siemens

The ACSES was initially designed to work in conjunction with existing cab signaling systems. The ACSES acts as an overlay, enforcing predefined civil speeds and ensuring positive stops at all interlockings when the cab signal receives a restricting aspect.

In contrast to continuous Cab Signaling products, which employ modulated carriers in the rails to provide a constant stream of information to the train, ACSES relies on an intermittent approach to information delivery.

Passive transponders are placed between the rails at convenient locations along the right-of-way. Each transponder is capable of transmitting "packages" of information to the train as it passes over. This information describes the civil speed restrictions between this transponder set and the next. In this way, ACSES can enforce civil speeds and positive train stops without a continuous data stream.

Since ACSES is an intermittent overlay type enforcement system, it can be integrated with the cab signal system or with the non-ATC/ABS through the ATC Interface Unit (AIU).

System Overview

AMTRAK's Northeast Corridor (NEC) is presently implemented with the Siemens "9-Aspect Cab Signal System". It can also be interfaced with other non-Siemens cab signal systems or non-ATC/ABS utilizing a Siemens ATC Interface Unit (AIU).

Cab Signal system ensures "Safe Train Separation" and "Signal Speed Enforcement," and non-ATC/ABS ensure "Safe Train Separation." At the same time, the ACSES acts as an overlay to the cab signaling system or non-ATC/ABS to enforce civil (track) speed restrictions, temporary (work zone) speed restrictions, and Positive Train Stops (PTS) at interlocking home signals.

ACSES utilizes passive (fixed) transponders at convenient wayside locations and sets of wayside transponders installed at home signals, distant signals, pre-distance signals, block points, or cut section locations to communicate the onboard ACSES's civil (track) speed restrictions for the territory ahead. This ensures that speeds are kept safe for the various conditions not caused by train occupancy (bridges, curves, tilting, etc.).

ACSES is a distance-based positioning system. This distinguishes it from cab signaling systems, which are speed-based. Positioning is critical for ACSES because civil speeds exist at specific locations along the right-of-way instead of signal speeds, which change with traffic flow.

ACSES establishes its position from the transponder sets it encounters. In between transponder sets, train positioning is ascertained by counting the speed pulses from the tachometer. This technique is known as "Dead Reckoning."

Any accumulated error is reset when the train encounters the next transponder set. Slip/Slide compensation adjusts for any error along the way. In this way, ACSES can maintain a high level of accuracy.

Enforcement on a Curve

ACSES incorporates alert and braking curves to provide profile-type braking characteristics for both civil speed restrictions and PTS.

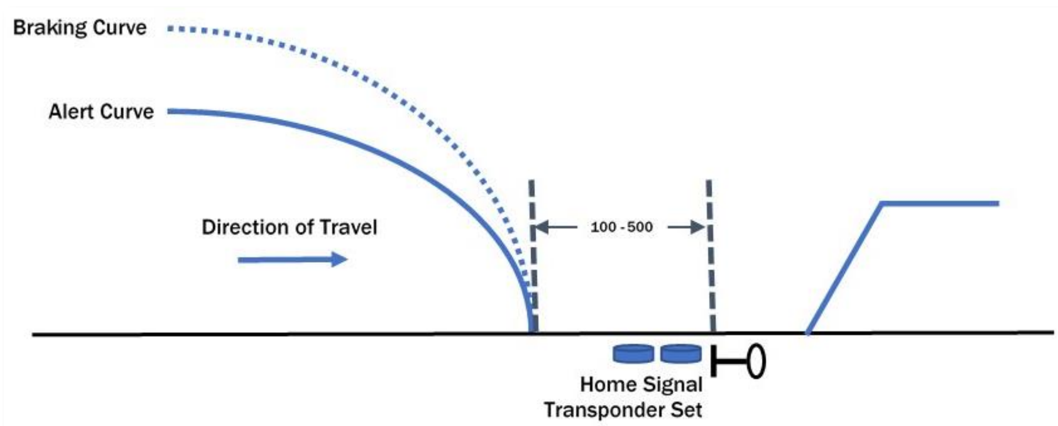

Figure 7 - Balise SSO, Braking Curve for Positive Train Stop at Home Signal[2]

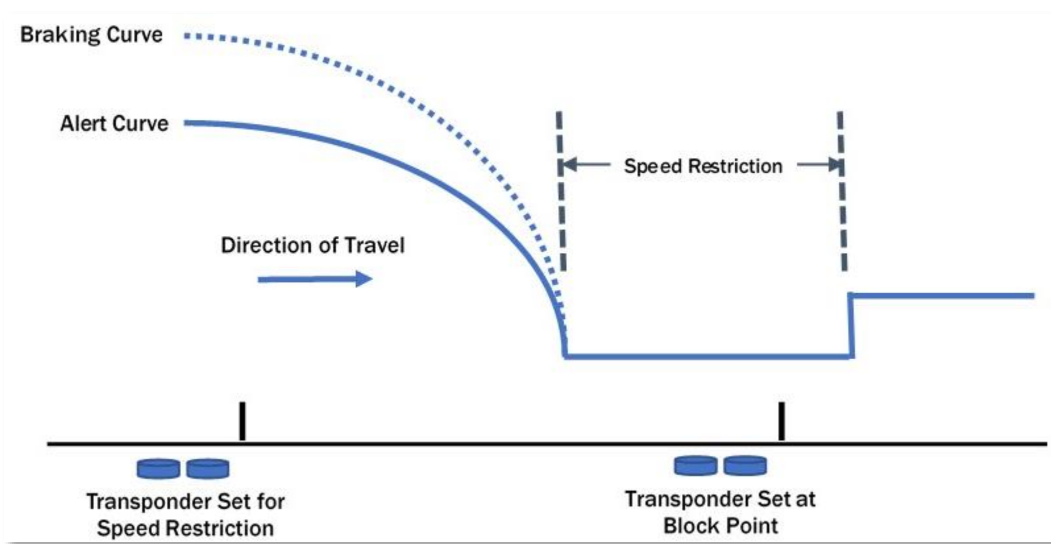

Figure 8 - Balise SSO, Braking Curves for Civil Speed Restriction[3]

[2] Source: Siemens
[3] Source: Siemens

When the train speed exceeds the alert curve, an audible alarm sounds, and the operator must apply brakes within 8 seconds to forestall a penalty. If he returns the train's speed to the civil speed limit, the alarm is silenced.

However, penalty brakes are immediately applied if the operator does not slow the train down and exceeds the braking curve. This penalty application is released once speed is at or below the civil speed. This is called a "Running Release."

ACSES Components

Transponders: Transponder sets are mounted between the rails and are composed of no less than two (2) and no more than four (4) physical transponder devices. This is done to improve reliability, increase information capacity, and automatically identify traffic direction. Transponder sets are not required to be located at the start of civil speed restrictions. They can be placed at convenient locations such as signals or cut sections where access to track crew. Information contained within the transponders points to the start and duration of civil speed restrictions ahead. The transponders are passive devices requiring no wayside power supplies. Their programming is accomplished by means of a "plug" that is inserted into each transponder. The energy needed to activate the transponder is transmitted by an antenna mounted underneath the vehicle. The antenna then picks up the information contained within the transponder's "plug." Each transponder set is "linked" to the one before it and the one after it. ACSES uses the linking distance to know when to expect the next transponder set as the train transverses transponder sets. By this method, missing transponder sets are detected.

Axle Generator: Speed pulse information is supplied to ACSES via a Siemens-designed end-of-axle generator or a similar type of speed pickup. Using a high-resolution variable reluctance speed sensor and a 60-tooth gear produces a signal to allow accurate train positioning (better than 1%) and speed measurement. The axle generator also contains a variable reluctance speed sensor with a 40-tooth gear available with an ATC system.

Antenna: The onboard antenna provides a field-proven means by which transponders can transfer information to the ACSES onboard computer. The antenna is mounted under the vehicle and is connected to the ACSES on-board computer. The antenna is turned on when the train is in motion and continuously transmits a sweep frequency down to the tracks. When the train passes over a transponder, the carrier powers the transponder, sending a signal back to the train with coded information representing the restrictions ahead. The antenna features mechanical and electromagnetic protection plates on all surfaces to channel the electromagnetic field radiation properly, except the bottom where the electromagnetic field is transmitted.

ACSES On-Board Computer on Cab Signal system: The ACSES onboard computer employs the same distributed micro-controller architecture used in the 9-Aspect cab signaling systems. Several half-height circuit boards are integrated into a single lightweight card file, comprising the ACSES onboard computer and the antenna interface. The circuit boards handle all the digital and serial I/O processing and the system logic and event recording functions. The ACSES system logic was designed for AMTRAK and is being utilized on all locomotives that run on the NEC, including the Acela™ high-speed trains and tenant locomotives, and is the same across all these railroads. The ACSES onboard computer system logic provides departure test capability and can be configured for a given vehicle by PC interface software. This PC software is also be used to download event data from the event recorder located within the ACSES card file. The ACSES onboard computer is a vital system. It employs both hardware and software crosschecking techniques to ensure critical operation. These techniques were developed by Siemens and are used in the 9-Aspect Cab Signal system, not to mention several other ATC products already in service.

ACSES On-Board Computer on non-cab signal/ABS systems: The onboard computer and civil speed/PTS enforcement system are similar to the cab signal system above except that the speed control input will be by transponder only; there is no cab signal speed code input for this type of application.

Positive Train Stop (PTS)

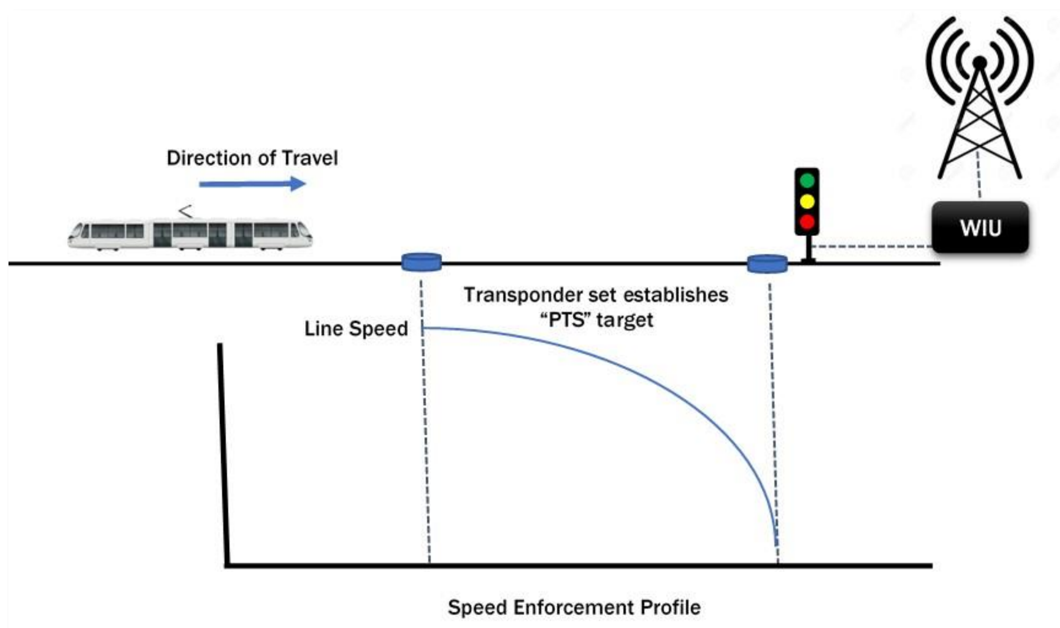

Figure 9 - ACSES Positive Train Stop Function Prior to Each Signal[4]

One of the most critical and sought-after features of ACSES is its ability to provide

[4] Source: Siemens

PTS. Current cab signal technology only allows for a restriction aspect of 20 mph when approaching a red home signal that may call for a stop and proceed or a complete stop. ACSES implements the PTS by targeting a stopping point just ahead of the home signal and enforcing train speed using its braking curves. Violation of the braking curve results in brakes being applied. Once stopped under a PTS, the operator pushes the Stop-Bypass button after receiving permission from central control to release the train.

Summary of Characteristics

- No Continuous Communication Required
- Passive Transponders (No External Power Supplies Required)
- Braking Curves Instead of Time
- Train Type Dependent Braking Curves
- Grade Compensated Braking Distances
- Permanent Speed Restrictions
- Temporary Speed Restrictions
- Positive Train Stop at Interlocking
- More Restrictive Braking Curves for PTS
- Missing Transponder Detection Through "Linking"
- Overspeed Detection & Running Release
- Integrated Operator Display
- On-Board Departure Test
- On-Board Data Logger
- Vehicle Parameters Configurable by Laptop PC

Case Study: Trainguard-MT by Siemens

Trainguard-MT Intermittent train control (ITC) is an intermittent track-to-train communication that allows fixed-block operation with continuous supervision. The intermittent train control level can be used for parts of the line with lower headway requirements or as a temporary system during refurbishment and switchover periods. When lines are refurbished, Trainguard-MT can be used as an overlay system for existing systems. This solution offers enhanced performance while preserving existing investment and minimizing disruptions to revenue service. Due to its open system architecture and standardized interfaces, Trainguard-MT is designed to work with other installed signaling systems and rolling stock. Step-by-step refurbishment starting with intermittent train control, which is later upgraded to the continuous train control level (CBTC), is also possible. Headways and the safety of existing systems can be improved by connecting balise to existing trackside signals to implement Trainguard-MT with intermittent communication.

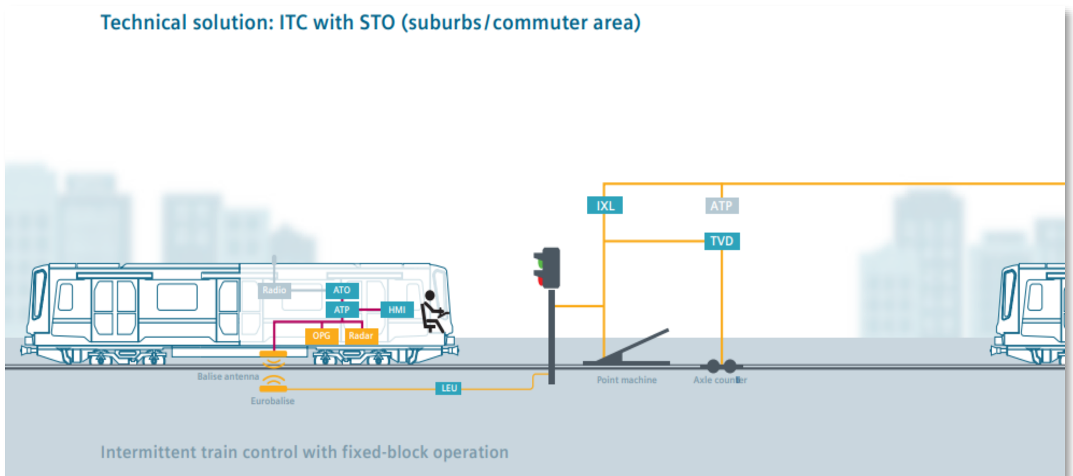

Figure 10 - Trainguard-MT Intermittent Train Control[5]

Balise and lineside electronic unit: The European Train Control System (ETCS)-compliant Trainguard Eurobalise is used for intermittent track-to-train communications. The balise system uses a transmission technique based on inductive coupling and data transmission with frequency-shift keying.

Case Study: PZB2X2 ATP System by BBR

The PZB2X2 ATP system, by BBR Verkehrstechnik GmbH ("BBR"), has been used worldwide on about ninety installations, including the MBTA's plans to implement this system in its Green Line Train Protection System.

This system is designed to increase the safety of the riding public by protecting train movements, preventing red signal overruns and train-to-train collisions on tracks used for passenger service. This is accomplished by installing a bi-directional wayside balise in front of vital wayside signals in areas of temporary or permanent speed restrictions and other danger points. The system influences the train based on its present speed, the track geometry, and the aspect of the next signal. If necessary, the system automatically initializes graded actions from acoustic warnings by enforcing safe speed profiles by operational braking to initiating forced braking if a vital signal's stop aspect has been overrun.

[5] Source: Siemens

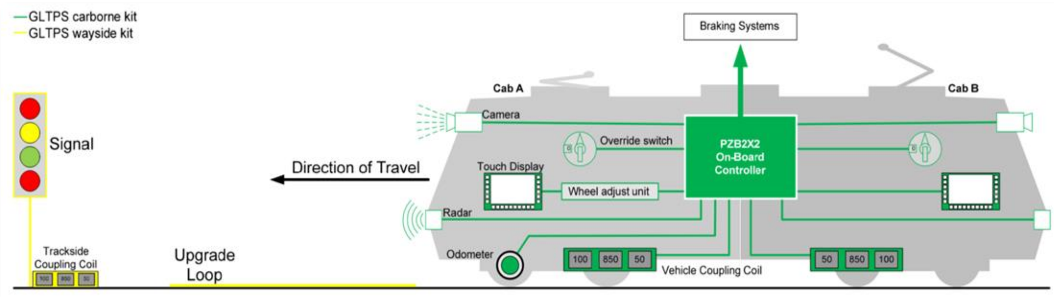

Figure 11 - PZB2X2 System Architecture[6]

System Components

Track mounted balise can be configured to transmit static and dynamic information.

Onboard: vehicle coupling coils for communication with trackside devices, odometer for precise speed and distance monitoring, control unit processes odometer data and retrieved ATP telegrams, touch display services as an interface for the operator, double speedometer for indicating actual and permissible speed. Bosch Forward Collision Warning System, including the radar sensor & vehicle front-mounted camera, can be installed to induce a service braking when a train or a road vehicle ahead is detected.

System Operation

Vehicle coupling coils receive data from the wayside balise. The binary data is transmitted in messages using Frequency Shift Keying (FSK). The power for the balise is provided by the vehicle coupling coil via a magnetic field oscillating at 100 kHz. This inductive near-field energy transfer allows all wayside balise to operate without any form of wayside power supply. The 100 kHz unmodulated signal is permanently transmitted as long as the vehicle coupling coil is powered. The PZB2X2 system also utilizes a 50 kHz subsystem which acts as the vital part of every signal balise. The 50 kHz subsystem monitors the faultless function of the wayside balise via an inductively coupled resonant circuit.

Before entering the ATP section, the train is in Initial Run Mode. Once inside the ATP section, the train receives the Balise telegram comprising the track section's speed profile. The speed will be adjusted on defined positions. Exceeding speed limits would cause a graded system reaction; a stop signal overrun would prompt an emergency braking.

[6] Source: BBR

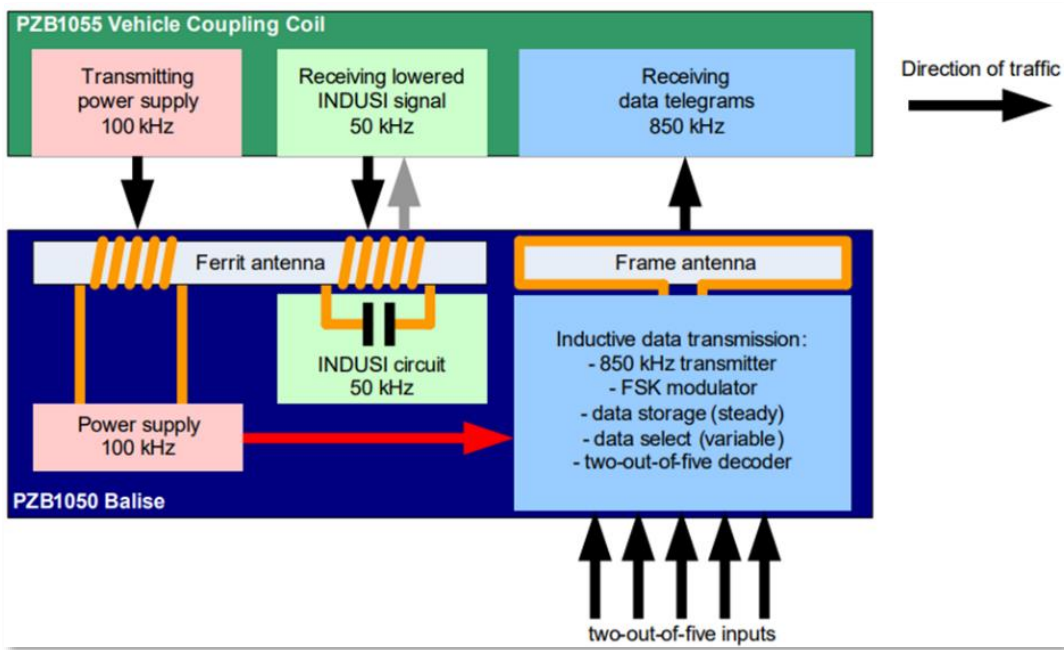

Figure 12 - PZB2X2 Balise and Vehicle Coupling Coil[7]

[7] Source: BBR

CBTC SSO Technology

The central concept of CBTC based SSO is that the train receives regularly updated information about its location via GPS and where it can safely travel, also known as movement authorities, via radio. Equipment on board the train then combines this information with its speed, direction, and track profile to enforce this movement authority, preventing unsafe train movement. This technology may work in either dark territory or signaled territory, and they use GPS navigation to track train movements. The objective is avoidance of train collisions, unprotected worker zones, train movements through incorrectly locked points, and train integrity failures. According to the track profile and current signaling status, these targets are achieved by setting correct speed restrictions and train stop locations.

This technology uses a distance-to-go braking concept; the following train would generate an onboard speed-distance profile based on worst-case braking and other conditions. If the train speed is below the profile speed, which decreases with block penetration, the train can enter the second or “buffer” block. Eventually, the train will stop, but at a location much closer to the first train, allowing for closer headways.

Case Study: I-ETMS by Wabtec

System Description

The Interoperable Electronic Train Management System (I-ETMS) is a vital, safety-critical, “overlay system.” Used in conjunction with existing methods of operations (e.g., CTC, TWC, ABS, TWC-Non-Signaled) that interfaces to existing signal systems, wayside devices, and office train dispatching systems via multiple communications links. I-ETMS provides the means to enforce compliance of movement authorities, speed restrictions, work zones, and switch positioning while retaining existing field signal system and office train dispatching system functions as the primary means of maintaining train separation and protection. The I-ETMS system is designed to support different railroads and their particular methods of operations. It is intended to be implementable across a broad spectrum of railroads without modification. Customization for individual railroads is accomplished by modifying the value of several different variables that reflect separate railroad operations. This design approach supports interoperability across railroads as I-ETMS equipped locomotives apply consistent warning and enforcement rules regardless of trackage ownership.

Main System Components

I-ETMS is made up of four unique segments: The Office segment, the Wayside Segment, the Communication Segment, and the Locomotive segment.

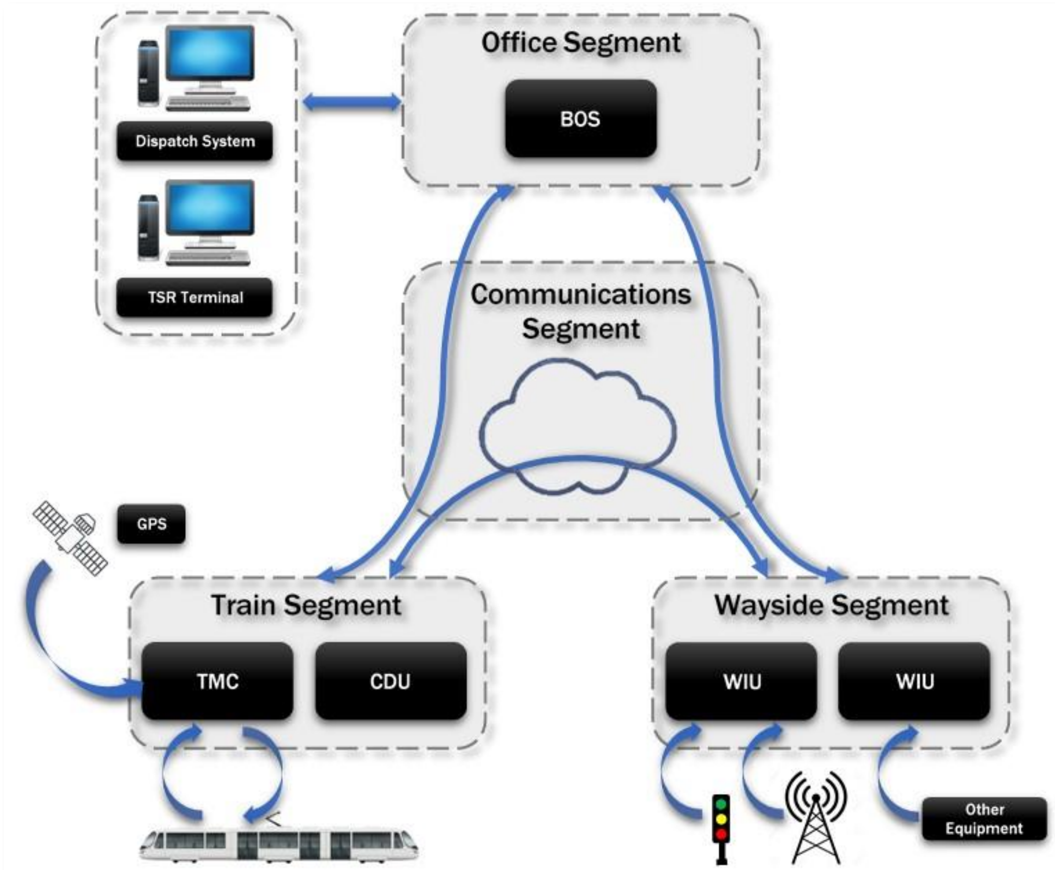

Figure 13 - I-ETMS System Segments[8]

Office Segment

The office segment is comprised of one or more Back Office Server(s) (BOS). It interfaces with other railroad back-office systems or applications, the railroad dispatch system, and the locomotive and communications segments. The office segment serves as a conduit for information conveyed to the locomotive segment where the system's vitality resides.

The office segment accepts mandatory directives and other information generated by the railroad's dispatching system and other railroad information systems and provides it to the locomotive segment. The interface between the office segment and railroad

[8] Source: Wabtec

dispatching and railroad information systems may be proprietary to a particular railroad. However, the office segment normalizes the operational data provided by a specific railroad's dispatching and information systems for exchange over an interoperable interface with the Locomotive segment.

In the current I-ETMS design, no safety-critical functions have been allocated solely to the BOS. The office segment data delivery function is non-vital in the overall architecture as the vital locomotive segment protects itself from potential hazards caused by data delivery failures. The office segment provides a non-vital check of the reasonableness and integrity of data received from external sources and delivers data to the Locomotive segment; however, the locomotive segment provides a vital range check.

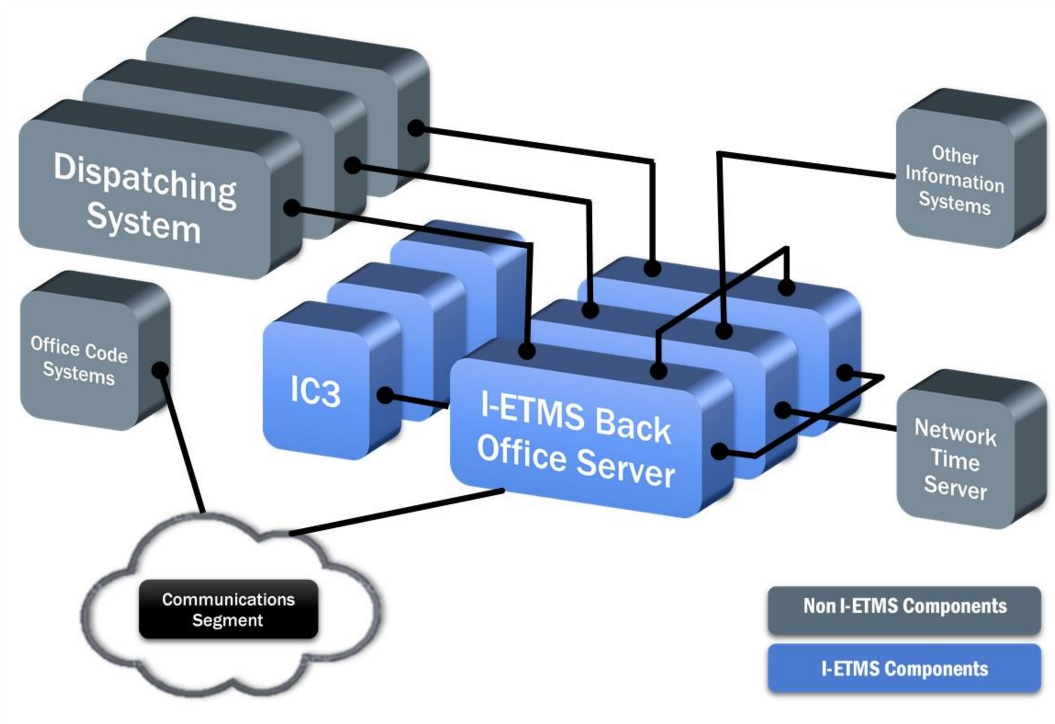

Figure 14 - I-ETMS Office Segment Configuration[9]

Wayside Segment

The wayside segment monitors and reports switch position, signal indications, or status of other monitored wayside devices directly to the locomotive and office segments using one or more radio networks. The wayside segment consists of traditional signaling equipment to which Wayside Interface Unit (WIU) function has been added. The wayside segment consists of those signaling appliances located in the field whose status impacts I-ETMS operations, along with any WIUs used to

[9] Source: Wabtec

monitor and report their status. Such appliances include interlocking controllers, signal controllers, switch circuit controllers, track circuits, track/route hazard detectors, or other field devices. Wayside segment components may exist in either signaled or non-signaled territory.

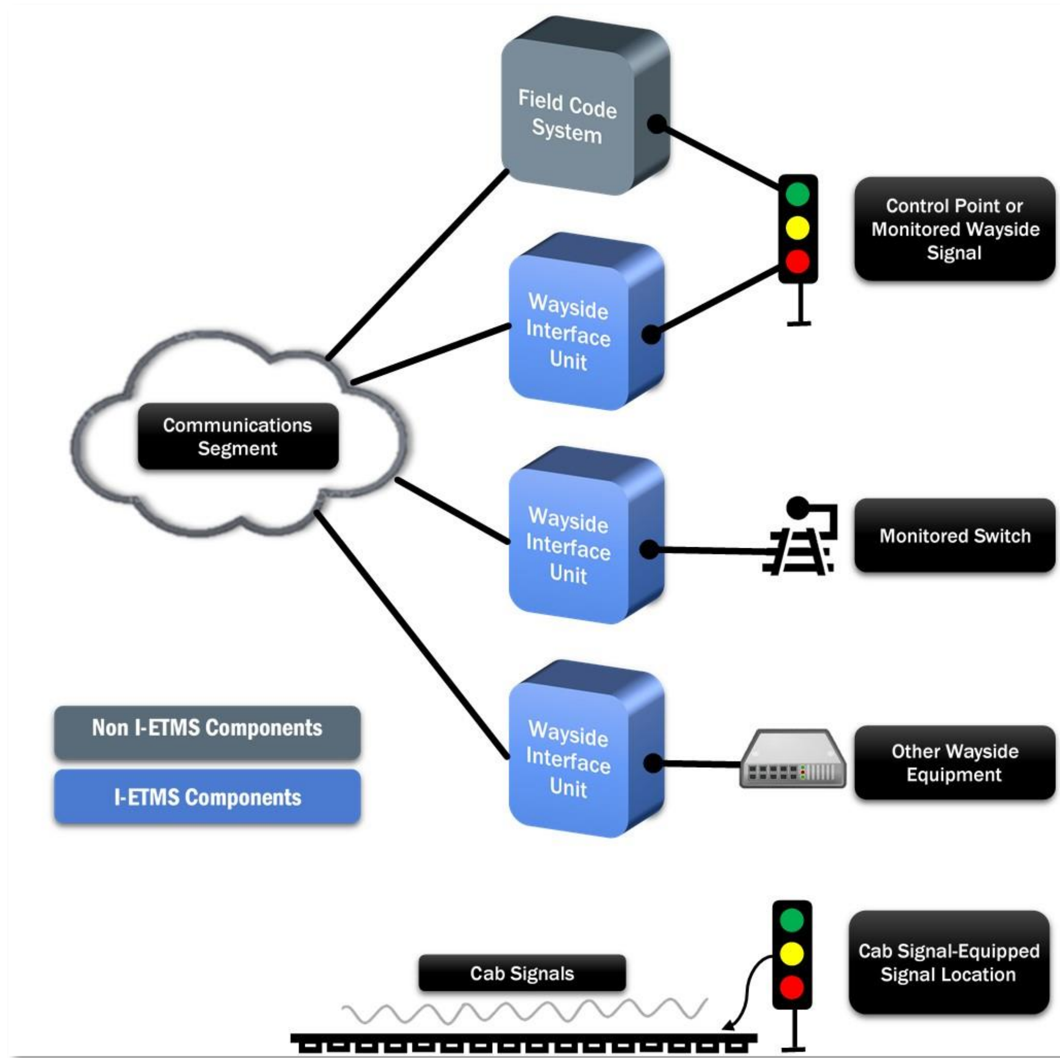

Figure 15 - I-ETMS Wayside Segment Configuration[10]

Wayside device status may be provided through three different configurations:

WIU-connected: A WIU is directly connected to a wayside device that publishes its status to the locomotive and office segments via the communications segment.

Office-connected: The wayside device status is forwarded to the office segment, relaying it to the locomotive segment.

Cab Signals: The locomotive segment can obtain wayside device status by monitoring

[10] Source: Wabtec

the onboard cab signal system.

Hazard detectors may or may not be integrated with a signal system. When combined with a signal system, a hazard detector will cause the attached track or signal control circuit to assume its most restrictive state upon detection of a potential hazard.

Communications Segment

The communications segment consists of a messaging system and multiple wired and wireless networks through which messages are exchanged between the locomotive, wayside, and office segments. The deployment of multiple wireless network technologies, as part of the communications segment, is used to maximize its capacity, throughput and to mitigate coverage issues.

Wireless networks that are planned as part of the initial deployment with I-ETMS include the following:

Private narrowband radio network (Interoperable standard)

- Broadband - Wi-Fi network infrastructure deployed by railroads
- Cellular and satellite - Public wireless data networks

Other wireless networks may be added, but railroads must deploy the data radio system to achieve interoperability in the communications segment.

The messaging system is designed to allow applications in the back offices, locomotives, and waysides to communicate in an interoperable fashion across railroad boundaries. The messaging system, known as Interoperable Train Control Messaging (ITCM), is a messaging solution based upon open-source software that has been customized to meet the requirements of I-ETMS. The ITCM is a loosely coupled, asynchronous message delivery system. Wayside, locomotive, and office applications communicate by simply addressing messages to one another and handing them off to the ITCM for delivery without being concerned about how messages are routed through the system.

The messaging system insulates the I-ETMS application from the underlying communications networks of the communications segment. It manages access to the available wireless networks to ensure that bandwidth is used efficiently and that I-ETMS message traffic has priority. The messaging system also supports the transfer of messages between railroad offices and allows the deployment of shared wireless infrastructure.

The locomotive segment can dynamically subscribe to receive the WIU status messages from the Wayside Status Relay Service (WSRS). In this configuration, the status of a wayside device is relayed to the locomotive segment via the WSRS. The WSRS runs as an application located in the back offices that accepts the status message published by the WIU. When the WSRS receives a status message, it looks up the subscriptions for the corresponding WIU and forwards it to the subscribing Locomotive segment.

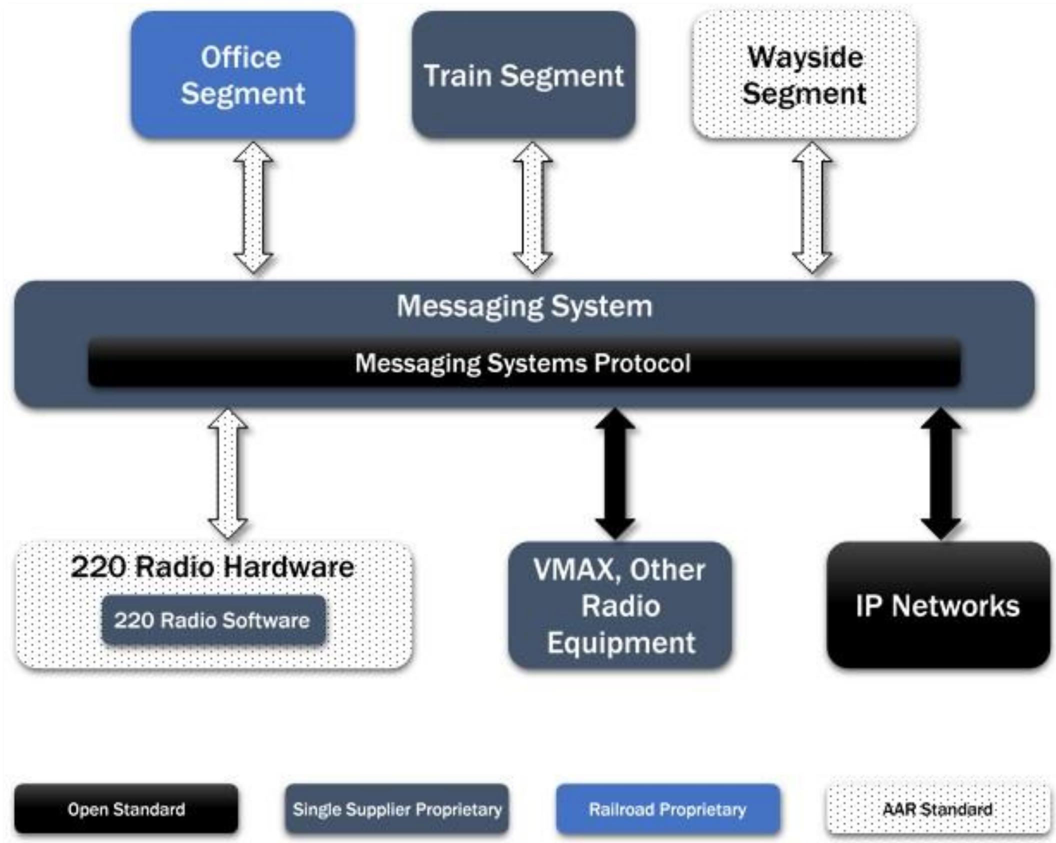

Figure 16 - I-ETMS Communications Network Architecture[11]

Locomotive Segment

The locomotive segment refers to a set of independent onboard hardware, software, and devices that interface with locomotive control equipment (e.g., air brakes, train line) and includes a Train Management Computer (TMC), a Computer Display Unit (CDU), a Locomotive ID module, a GPS receiver, and a brake cut-out switch.

The locomotive segment accepts movement authorities, temporary speed restrictions, other mandatory directives, train consist data, and other information from the office segment. The locomotive segment may directly receive switch position and signal indications via Peer-to-Peer communication with the wayside segment. The locomotive segment interfaces with other locomotive devices, including an event recorder, train line data sensors, horn circuits, brake systems, cab signal systems (if

[11] Source: Wabtec

equipped), and communication segments.

Multiple train control processing modules, executing similar application software, are used to perform all train control functions such as determination of current position, calculation of warning and braking distances, management of limits or restrictions conveyed by verbal or electronic mandatory directive or signal indication, management of off-board communications, and communication with the CDU. Graphical displays on the CDU reinforce situational awareness to promote compliance with movement authorities and speed restrictions safely.

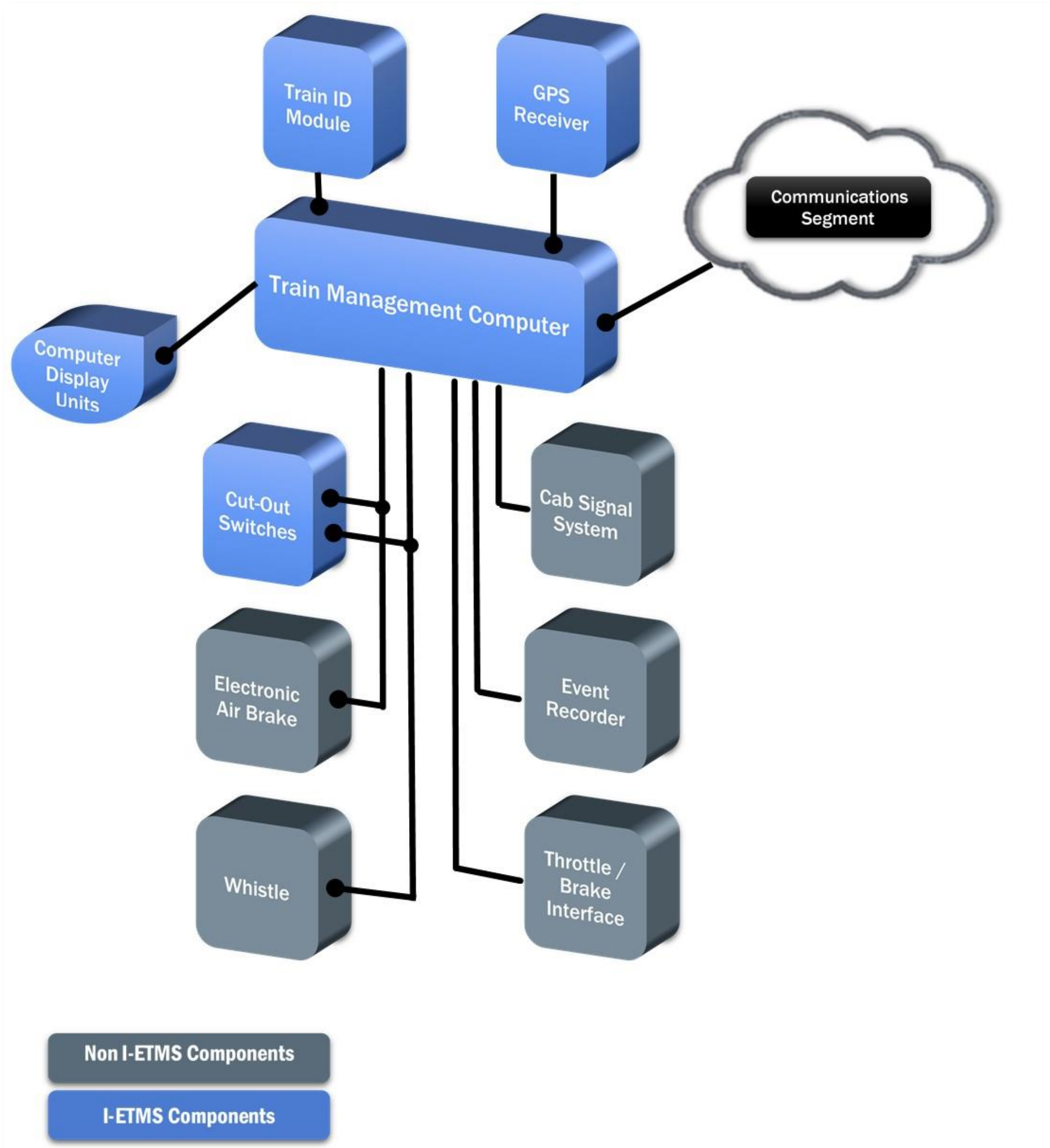

Figure 17 - I-ETMS Locomotive Segment Configuration[12]

[12] Source: Wabtec

The locomotive segment includes diagnostic capabilities to identify and report module-level failures. Failure reports are transmitted to the back office when possible. They may be forwarded to the railroad's existing maintenance or monitoring systems to facilitate the issuance of repair or trouble tickets for critical faults and prevent non-critical faults from degrading further. In an acute failure, the locomotive segment would have to be manually cut out to allow locomotive movement until the failure can be repaired.

The locomotive segment utilizes one or more external GPS receivers to determine the location and to drive the train control navigation algorithms. The standard receiver used in this system provides 10m (95%) accuracy under normal operation with 3m (95%) accuracy when WAAS correction information is available through the satellite system. This accuracy level and navigational aids such as switch position provide the precision required for I-ETMS to determine on-track position. A receiver's position and speed will be validated against the previous position and speed information to discard erratic reports.

The locomotive segment provides status information and position reports to the office segment and acknowledges messages received from the office segment.

The I-ETMS track database is a component of the system configuration. This database contains data elements, some of which are safety-critical, that provide the information required to support the I-ETMS navigation function and enforce authorized train movement. The database originates from railroad track data obtained from multiple sources external to I-ETMS. The railroad track data must be formatted to interface with the locomotive segment Train Management Computer (TMC).

Work Zones Protection

The dispatching system creates these track bulletins to identify specific locations where a train crew must obtain authorization from an Employee-In-Charge (EIC) to enter and proceed through the work zone limits. Work zones are bulletined in effect between specific milepost locations and times. They are used to protect roadway workers, large-scale production gangs, etc., performing maintenance or working on or about the track. Authority to enter and move within the limits of a work zone may only be granted by the Employee In Charge (EIC) specified in the track bulletin and must be repeated by the employee receiving authorization. The EIC may impose restrictions upon train movement within the limits of a work zone, such as a reduction in speed or a requirement to stop at a particular location. Trains may not be permitted to make reverse movements within the work zone limits, depending upon the railroad rules in effect.

Satellite-based SSO Technology

Case Study: ITCS by GETS/Alstom

In Michigan, AMTRAK uses global navigation satellite systems (GNSS) based ITCS in commercial operation for 145 km/h passenger trains on the New Bedford – Kalamazoo section of its Chicago – Detroit line. The Alstom Incremental Train Control System (ITCS) is a virtual block-based signaling system that uses GPS to determine train location. This method eliminates the need for trackside devices such as balise and physical train detection such as track circuits or axle counters. As signals are transmitted by virtual means and not on the trackside, it requires minimal infrastructure on the ground. It can be deployed either as an overlay to an existing signaling system or as a standalone solution. As such, it can be configured to any project requirements, communication system and radiofrequency, and can be expanded as railway operations grow. The ITCS speed enforcement and vital positive stop functions mean that the train will never go past a boundary or exceed the safe limits of operation. An additional advantage of virtual blocks to physical blocks is that they can be made to any size, increasing the capacity of a line and, therefore, its throughput without adding railway infrastructure.

- Train knows position from GPS
- Wayside equipment provides the status of track switches, track circuits, and signals to train via radio
- Train enforces signals according to rulebook train enforces civil speed limits from database
- Crossings activated by radio to support high-speed trains
- Temporary slow orders delivered to train via radio and enforced to protect track sections and workers
- Scalable and flexible virtual block signaling
- Ultra-low wayside infrastructure
- Proven in harsh and remote environments
- ITCS includes a unique Portable Remote Terminal (PRT) for EIC of the work zones. A PRT provides the ability to view the status of all active MD and provide a means to transmit an electronic authorization to ITCS-equipped trains to enter the work zone under their control. The engineer, through a soft button on the locomotive CDU, must accept this authorization. The engineer may only take the authorization once they have received verbal radio authorization from the dispatcher or EIC. Communication between the ITCS EIC portable equipment and the ITCS onboard is done through a cellular link to the dispatch system, the Schedule Serve Subsystem, and the ITC radio network.

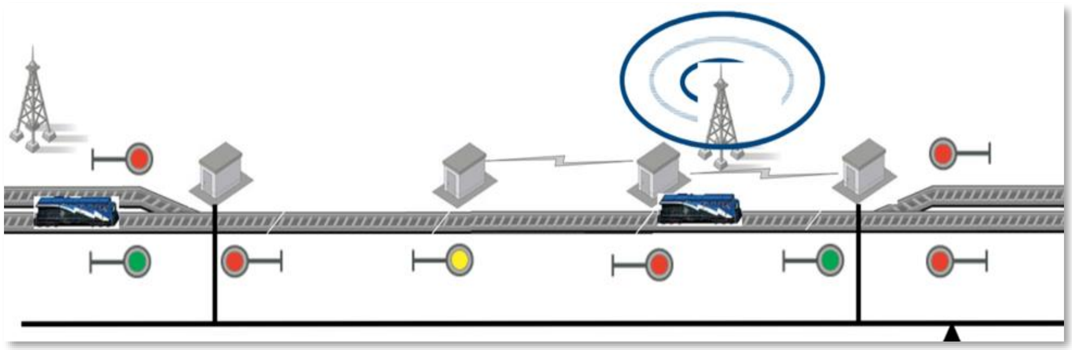

Figure 18 - ITCS Overlay on Block Signals[13]

The schedule server subsystem has been used to facilitate this communication to ensure the BOS interface remains unmodified for I-ETMS-equipped trains. The EIC PRT cannot be used to apply a speed restriction to the locomotive OBC directly. Suppose the EIC requires a train to operate through a Form B (mandatory directive protecting men and equipment) with a speed restriction. In that case, the EIC prearranges that speed restriction with the dispatcher, who then places a speed restriction (Form A-speed restriction) for the system to enforce the restriction.

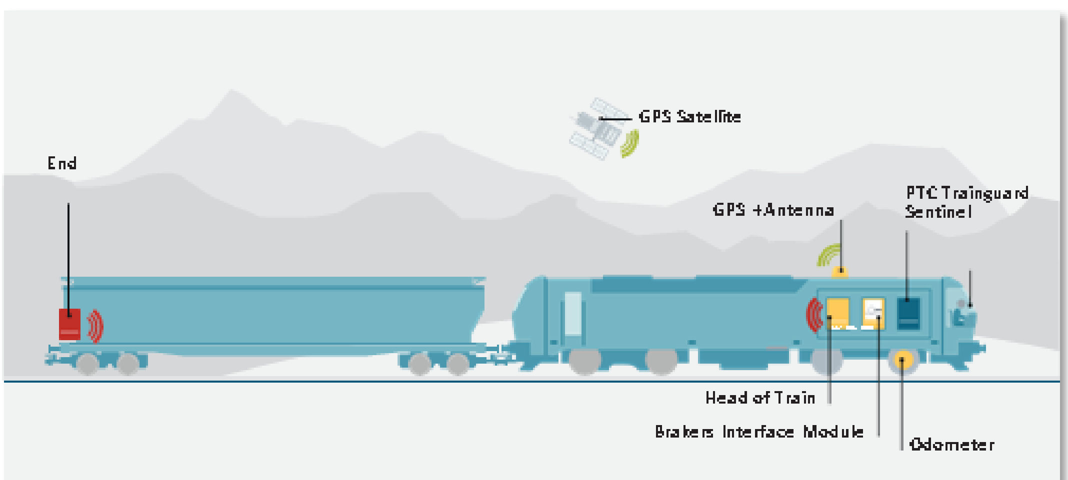

Figure 19 - ITCS as a Stand-alone System[14]

Case Study: Trainguard Sentinel by Siemens

Siemens develops a similar satellite-based stand-alone solution Trainguard Sentinel. This system focuses on an easy-to-enter option while offering seamless upgradability to gain operational efficiency. Trainguard Sentinel includes an onboard system, such

[13] Source: Alstom
[14] Source: Alstom

as a docked-in tablet solution or a fixed installed onboard computer. The system delivers speed monitoring and a time-optimized speed profile. Trainguard Sentinel also includes the onboard GPS positioning and an odometer sensor to determine location. The system can be expanded with optional brake interfaces and train integrity monitoring using head-of-train and end-of-train devices. It also uses wireless communication for voice and data. It regulates speed, logs the operator's actions, and monitors the train's position in areas with satellite signals. Using speed sensors, the train position can be observed at the end of the trip by checking the log, even for regions without satellite position coverage. In addition to all the features of the stand-alone solution, the integration of the Operation Control Center (OCC) allows movement authority, temporary speed restrictions, and trans-parent train position and data.

Dispatchers working at the control center can manage the network by setting and sending movement authorities or temporary speed restrictions to the trains via a radio network. The control center also displays the railway layout to show the position of each train and the status of movement authorities to dispatchers. Train locations are updated via their satellite positioning system, odometry, and trackside vacancy detectors (if available).

As soon as a movement authority is set, point machines and signals are selected (if available) via object controllers, and information is sent to train over the radio. When the train receives any movement authority via radio, this information is computed onboard, and the onboard monitors the stop locations and speed limits. All relevant driving information is displayed to the driver in an HMI screen, and onboard keeps monitoring train integrity with the end-of-train device and supervising speed, applying brakes if needed until the train reaches its assigned destination.

These solutions can also be adapted to existing interlockings or serve with other wayside products. The Trainguard solution, for example, can include electronic interlockings, point machine detection, speed monitoring, hot box/axle detectors, derailment detectors, or track vacancy devices such as axle counters or track circuits. It may also integrate wayside signals and road crossings. Trainguard can interface with the existing wayside systems or provide new wayside solutions to enhance the safety and operation of the trains.

CBTC Moving Block Technology

Traditional signaling systems detect trains in discrete sections of the track called 'blocks,' each protected by signals that prevent a train from entering an occupied block. Since every block is a fixed section of track, these systems are called fixed block systems.

A CBTC system is a "continuous, automatic train control system utilizing high-resolution train location determination, independent from track circuits; continuous, high-capacity, bidirectional train-to-wayside data communications; train borne and wayside processors capable of implementing automatic train protection (ATP) functions, as well as optional automatic train operation (ATO) and automatic train supervision (ATS) functions," as defined in the IEEE 1474 standard. The main objective of CBTC moving block technology is to increase track capacity by reducing the time interval (headway) between trains. In a moving block CBTC system, the protected section for each train is a "block" that moves with and trails behind it. It provides continuous communication of the train's exact position via radio, inductive loop, etc.

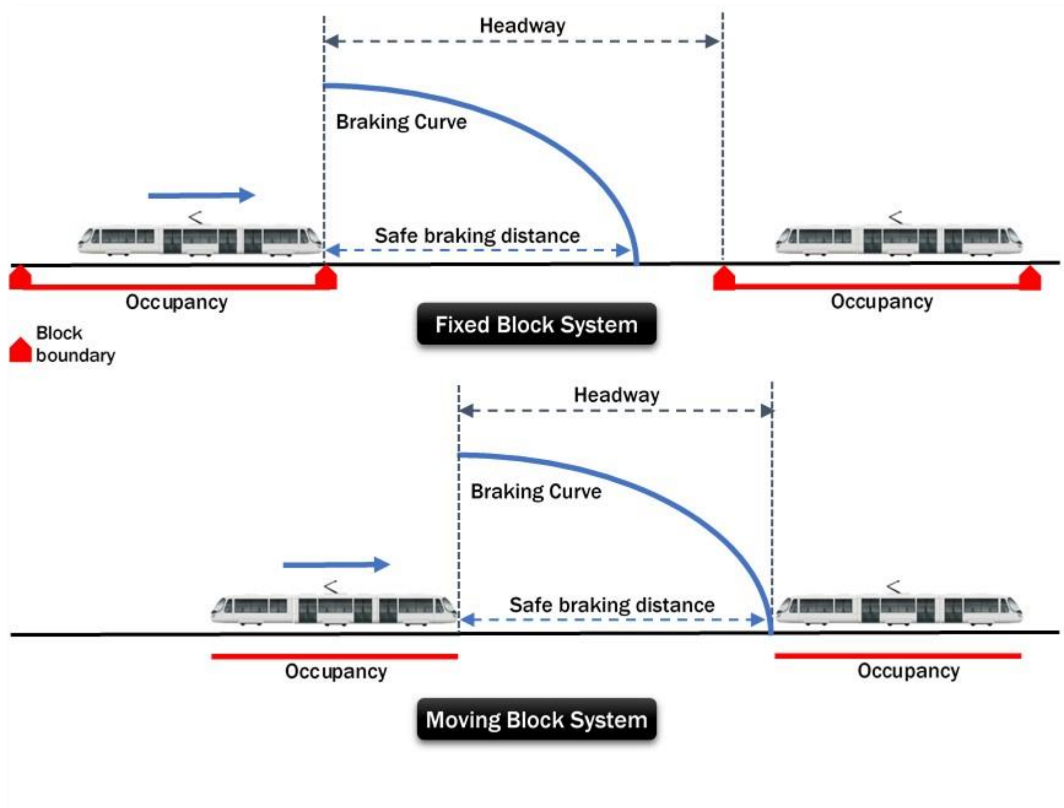

Figure 20 - Fixed Block vs. Moving Block

Previously, CBTC had its former origins in the loop-based systems developed by Alcatel SEL (now Thales) during the mid-1980s. These systems, also referred to as transmission-based train control, used inductive loop transmission techniques to train communication.

Bombardier opened the world's first radio-based CBTC system at San Francisco airport's automated people mover (APM) in February 2003. A few months later, in June 2003, Alstom introduced the railway application of its radio technology on the Singapore North-East line.

In the modern CBTC systems, the trains continuously calculate and communicate their status via radio to the wayside equipment distributed along the line. This status includes, among other parameters, the exact position, speed, travel direction, and braking distance. This information allows calculation of the area potentially occupied by the train on the track. It also enables the wayside equipment to define the points on the line that must never be passed by the other trains on the same track. These points make the trains automatically and continuously adjust their speed while maintaining the safety and comfort (jerk) requirements. So, the trains always receive information regarding the distance to the preceding train and can adjust their safety distance accordingly.

CBTC technology is evolving, using the latest techniques and components to offer more compact systems and simpler architectures. For instance, with the advent of modern electronics, it has been possible to build redundancy so that single failures do not adversely impact operational availability.

Moreover, these systems offer complete flexibility in operational schedules or timetables, enabling urban rail operators to respond to the specific traffic demand more swiftly and efficiently and solve traffic congestion problems. Automatic operation systems can significantly reduce the headway and improve the traffic capacity compared to manual driving systems.

For a moving block system to work, the system needs a reliable train position and speed to calculate the safety zone surrounding the train. The system onboards the train continually calculates its position and transmits it, along with other data like speed, direction, and other onboard status data, to the wayside systems. In return, the wayside systems share data like maximum permitted speed and the current target point of the train, which is a point along the line that can be reached safely without any obstructions in the way. By advancing the target point of a train along the way, the train is safely guided to its next stop at a safe speed and a safe distance to the train in front of it. This way, trains can run much closer together, making it possible to run trains at a much higher frequency, even as short as one minute apart.

Case Study: SelTrac by Thales

SelTrac evolved from an early digital inductive loop-based train control system developed by Alcatel SEL during the mid-1980s. This technology was first used on the SkyTrain network in Vancouver, British Columbia, and the Scarborough RT in Toronto, Ontario. Thales now sells SelTrac from their Canadian unit. New versions were made for different markets.

The original SelTrac system was based on inductive loops that provided a communications channel and positioning information. SelTrac loops cross every 25 meters to form lozenge-shaped areas. The communications system on the vehicles can detect a phase change in the signal caused by these crossover points, allowing them to place themselves within a single one of these sub-loops. The vehicles broadcast this position information into the loops, along with IDs, speed, direction, and other data. When originally being designed, computers were expensive, and data storage was limited. SelTrac used on the ICTS systems centralized all control. After receiving location information from a vehicle, the blocks and safe target points for each were calculated, and this information was then broadcast back out through the inductive loop to be received by the vehicles. Onboard controllers used this information to calculate a safe speed to approach the next target point and modified its current speed appropriately. The system was designed to reduce the complexity and thus cost of the vehicle controllers as much as possible.

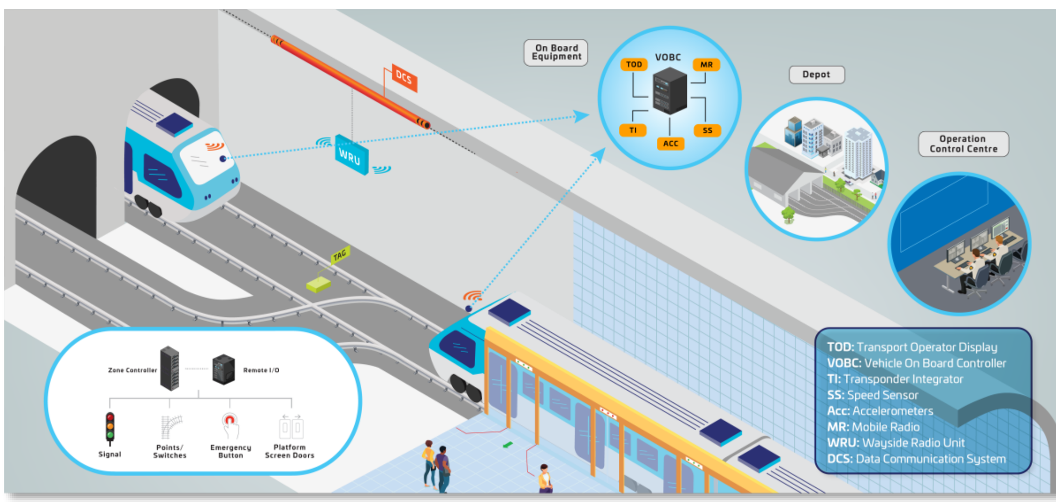

Figure 21 - SelTrac CBTC Basic Layout[15]

In modern systems, much more information can be stored in the vehicle controllers. These now know the layout of the track, speed limits, and other data. This allows the controllers to make better decisions about setting their speed or speeding up before an incline.

The latest SelTrac CBTC is SelTrac G8, a radio-based system. It includes a new digital architecture designed to be upgraded easily. A suite of enhanced services to support operators achieve maximum availability, and a next-generation position system (NGPS) uses inertial navigation, radar, and radio ranging – the same technology stack

[15] Source: Thales

used in the fully-autonomous operation. The NGPS is easy to deploy, already piloted this system on the New York City Subway.

Case Study: CITYFLO by Bombardier/Alstom

CITYFLO 650 is a CBTC, moving block ATC system. The system does not require track circuits and can be used as an overlay radio-based train control system to upgrade existing fixed block systems. It also eliminates wayside equipment due to its simple, reliable radio-based train-to-wayside communications systems, thereby permitting shorter, more consistent headways. To ensure continued operation of the previous track circuit-based Automatic Train Protection (ATP) system in parallel, an overlay approach was chosen by some customers. The ability to provide mixed-mode operation promised no interruption to service for passengers and provided low-risk migration to CBTC with the opportunity to test the new system in 'shadow mode.' This safe environment proved the functionality and safety of the new system, while the previous ATP still had complete control of the operation.

Key Achievements

Reduced headways and increased availability are vital contributors to the program to increase capacity and improve the quality of service.

The CBTC solution implemented as an overlay allows mixed-mode operation and seamless transition, resulting in no interruption to service.

Bombardier's customization of systems for customer environments simplified the transition to an entirely new signaling concept for end users.

Case Study: Urbalis by Alstom

In 2003, Alstom delivered its first radio-based CBTC in the North-East Line of Singapore.

Today, Urbalis has been installed on over 50 metro lines around the world. Urbalis is continuously being perfected to achieve the ultimate train control solution.

Key advantages include flexible and scalable control system architecture, based on moving block principle, which safely optimizes the maximum of available rail network capacity. This system reduces the headway between trains down to 60 seconds and consequently ensuring the system's higher efficiency and train frequency with minimal or zero passenger service disruption.

The new Urbalis Fluence integrates innovations that drastically simplify the signaling system by completely merging interlocking functions into a train-centric CBTC. Conversely, Urbalis 400 operates with traditional interlocking. Both solutions capitalize on a joint technological base that is constantly being upgraded, and they offer the highest level of safety.

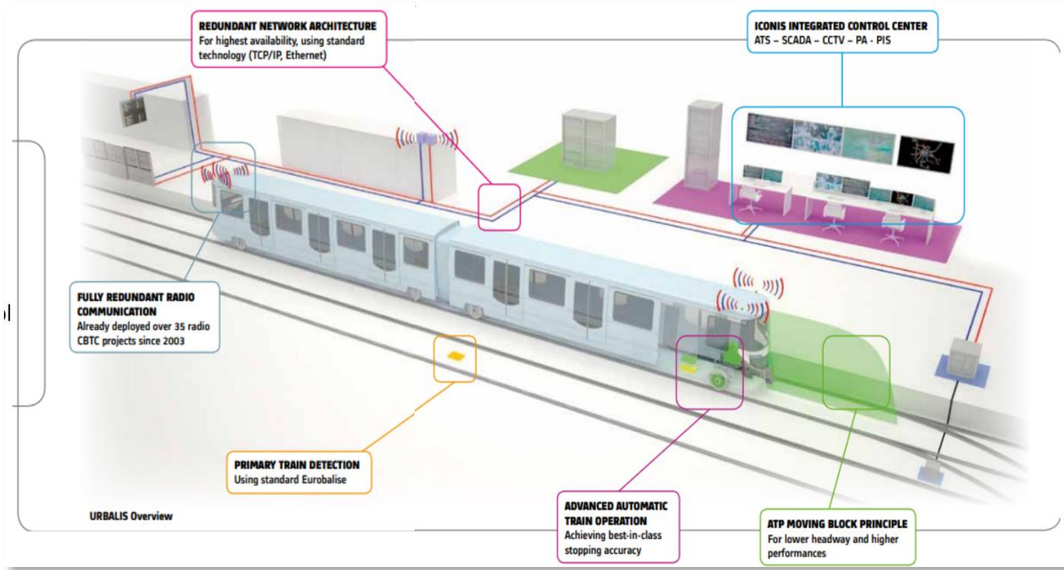

Figure 22 - Urbalis CBTC Basic Layout[16]

Case Study: Trainguard by Siemens

Trainguard MT

Trainguard-MT continuous train control (CTC): Trainguard-MT with continuous train control features a bi-directional radio transmission channel (CBTC) and actual moving-block functionality combined with comprehensive ATO capabilities. Train separation according to the moving-block principle results in minimum headways, thereby enhancing system performance significantly. Color light signals can be reduced to a minimum or even entirely omitted. In CTC operation, the energy consumption of trains is optimized by intelligent ATO algorithms.

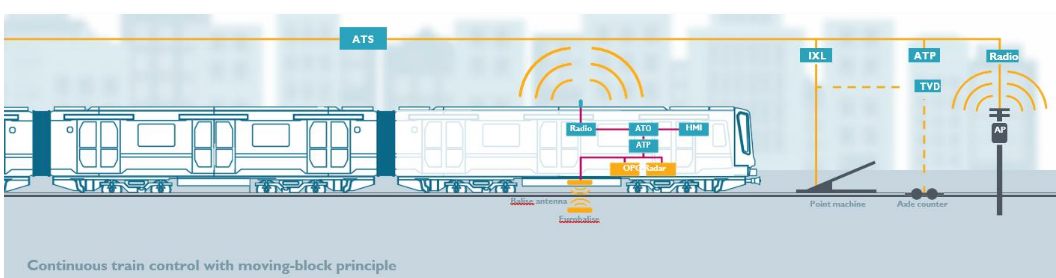

Figure 23 - Trainguard MT CBTC Basic Layout[17]

[16] Source: Alstom
[17] Source: Siemens

Trainguard-MT is designed to work with other installed signaling systems and rolling stock. Step-by-step refurbishment starting with intermittent train control, which is later upgraded to the continuous train control level (CBTC), is also possible. As performance requirements rise, Trainguard-MT allows cost-effective upgrading to higher system performance by adding components and subsystems such as radio communication for moving-block functionality. Thus, the headway and throughput are increased.

Subsystems of Trainguard-MT

Precise train locating using radar and odometer pulse generator: The radar sensor measures the train speed over the ground by applying the Doppler effect. The odometer pulse generator measures the distance by counting the pulses derived from wheel rotation. By using intelligent sensor fusion algorithms, precise detection of the train speed and distance is ensured. Therefore, Trainguard-MT can fulfill the ambitious stopping accuracy requirements of +/- 30 cm and less.

Remote connectivity and monitoring: The signaling system can be connected through a Data Capture Unit (DCU) as the one-way data gateway for the secure connection of the signaling network to a remote storage medium (server) over the IoT. Via MindSphere, the open, cloud-based IoT operating system from Siemens, operators can analyze and merge operational and historical system data, timetable information, weather forecasts, or major events in a city. This helps to improve the performance of your operation and the utilization of your assets. Furthermore, maintenance can be done more efficiently, and system availability can be increased. Intelligent analysis can reveal failures by predicting them in advance and fixing them before they happen.

Reliable Track Vacancy Detection (TVD): Trainguard-MT works without any track vacancy detection system. During regular operation, all trains report their position cyclically to the Trainguard-MT wayside units. In case of disturbances, the TVD can detect non-reporting trains so that operation can be restored to normal within a short time and with minimal interference. Furthermore, TVD can be used for mixed-traffic and non-equipped train operations. If required, the Clearguard ACM axle counters can serve as a secondary track vacancy detection system. Trainguard-MT also allows the use of other kinds of track vacancy detection systems (e.g., track circuits).

Ergonomic human-machine interface (HMI): The ergonomic human-machine interface is the operator's multifunctional console. It combines a high-resolution color TFT display, touch-screen operation, and audible feedback.

Airlink: Secure IP-based radio propagation for track-to-train data communications: Secure, reliable connectivity between trains and the wayside infrastructure is a fundamental requirement in a CBTC system. Therefore, Siemens has developed the Airlink radio communication system to ensure the continuous and smooth operation of its Trainguard-MT automatic train control system. Airlink supports all levels of automation from semi-automated to fully automated train operation and provides highly efficient train operation.

Trainguard Sirius CBTC

Operating principles

Trainguard Sirius CBTC is an automatic train control system designed on a virtual moving block principle using CBTC technology. Trainguard Sirius CBTC uses a digital radio system to provide a continuous, high capacity, bi-directional train-to-trackside data communication link. The basic operating principle of Trainguard Sirius CBTC is that each train is granted its Limit of Movement Authority (LMA). From the information contained in the LMA, the onboard equipment continuously supervises train speed to ensure that the LMA cannot be exceeded. To accomplish this, each train continuously reports its position over the digital radio to the trackside Block Processor (BP). The BP uses the position information from the trains and tracks status information from the interlocking to recalculate the LMA for each train. The LMA, together with track profile data, is sent via the trackside communications controller (TCC), based on moving block principles.

Passive Absolute Position Reference (APR) beacons, located along the track, are activated by the train as it passes over them. They provide information that allows the trains to determine their position to the optimum level of precision as they move along the line. The train's movement is fully automatically controlled by the automatic train operation (ATO) equipment. For not entirely driverless lines, a train attendant – not necessarily in the operator's cab – will control the train doors and train start functions through a touch-screen device acting as a Driver Machine Interface (DMI). Trainguard Sirius CBTC can also interface with Platform Screen Doors (PSDs) using a bidirectional data exchange between the trains and trackside equipment. This allows open/close commands to be coordinated between the PSDs and train doors safely and provides accurate train stopping. To operate such a system, a comprehensive set of automatic command and control functionalities must be available. To this end, Trainguard Sirius CBTC includes an ATS system developed by Siemens Rail Automation for its CBTC solution. The ATS integrates a set of programs and tools to implement a wide range of functionality, including traffic control, depot management, train wake/sleep, automatic regulation, integrated maintenance, incident report/replay, and operation simulators. The ATS is also constructed using an open architecture to provide simple integration with other railway control systems such as traction power control, passenger information systems, building management, environmental control, or any telecommunication system.

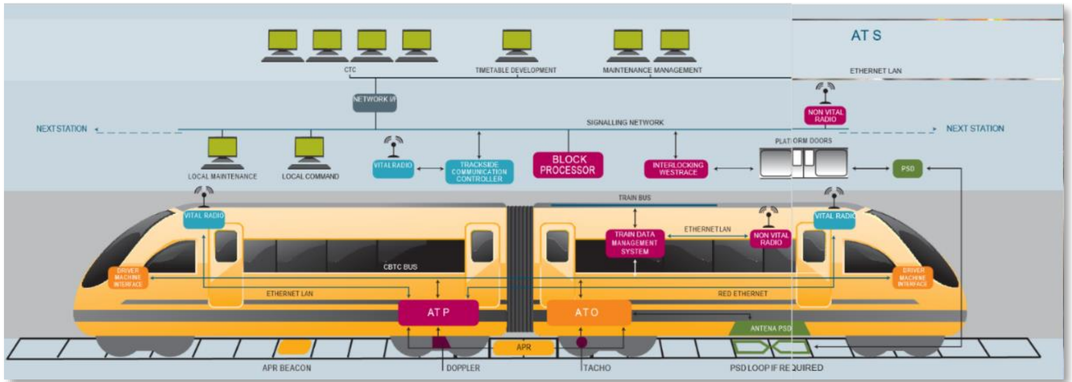

Figure 24 - Trainguard Sirius CBTC Basic Layout[18]

Main Characteristics

Digital Radio Communications: Trainguard Sirius CBTC uses a powerful bi-directional data transmission system for vital information. This system uses digital radio based on spread spectrum technology and internet protocol (IP) communication.

Architecture: The system architecture is open and distributed, allowing for easy application of Trainguard Sirius CBTC and its interfaces with other systems.

Flexibility: Trainguard Sirius CBTC can operate with other systems from Siemens Rail Automation on lines equipped with different Siemens Rail Automation systems speed signaled or distance to go.

Modularity: All the subsystems of Sirius perform specific functionality. This function enhances reliability and makes maintenance more straightforward, allowing each sub-system to be upgraded without affecting the overall system.

Connectivity: Trainguard Sirius CBTC uses Profibus and TNC standards for train carried equipment and IP-based communication for trackside equipment and track to train communication.

Safety and reliability: Trainguard Sirius CBTC has been designed according to European standards CENELEC 50126, 50128, and 50129. Vital functions are performed in both train-borne and trackside processors. Train location is determined to high resolution using passive beacons.

Availability: Trainguard Sirius CBTC uses a 2 out of 3 architecture. This configuration, combined with the high-level reliability of the individual components, results in availability figures over 99.99%.

Maintainability: Trainguard Sirius CBTC includes a centralized Maintenance Aid System (MAS) to facilitate diagnostic work, both train-borne and trackside. All fault

[18] Source: Siemens

and incident information are stored within the appropriate equipment and transmitted to the central maintenance system through a non-vital radio link.

Case Study: CBTC by Ansaldo/Hitachi Rail STS

From operator-based to driverless and unattended driving modes, and from new to refurbished lines, Ansaldo STS's CBTC solution, based on moving block technology, overcomes the limitations of conventional fixed block systems. Leveraging its experience in turnkey systems, maintenance, and operation of driverless metros, Ansaldo STS's CBTC solution is the best choice for customers demanding high levels of performance, automation, functionality, maintainability, and reliability for their transport systems.

The Ansaldo STS CBTC system is composed of the following significant subsystems and equipment:

- Central Automatic Train Supervision (ATS) subsystem
- Wayside subsystem, which includes zone controllers, database storage unit, and MicroLok® II interlocking controllers
- Car-borne controller
- Data Communications Subsystem (DCS)

The Ansaldo STS CBTC system will offer the latest technology, proven components, open interfaces, robust hardware and software design, and rigorous quality standards available today. When complete, the system will integrate the full complement of specified Automatic Train Protection (ATP), Automatic Train.

Operation (ATO), and Automatic Train Supervision (ATS) functions. The ATP functions provide fail-safe protection against collisions, excessive speed, and other hazardous conditions. ATO functions will fulfill essential train operation functions within the protection limits imposed by the ATP system. ATS functions will provide system status information, monitor system operations, and implement automatic control for various system functions.

The key feature of the Ansaldo STS CBTC system is high system availability. The system's high availability is a result of having traditional interlocking functions maintained on the wayside at each interlocking location using MicroLok II. The system will support safe train movements even if a zone controller fails. These safe train movements are enforced via the MicroLok interlocking controller and wayside LED home signals. In addition, if only the DCS fails, overspeed protection is executed along with positive stops at all red aspect signals.

Key Design Features:

- Five train operating modes ensures high availability of train movements
- Automatic driverless turn-back operation increases the efficiency of train movements
- Interlocking functions are wayside distributed permits the system to continue safely moving trains in the event a zone controller fails or communications between the zone controller and the train fail using the backup operating system
- DCS is dual path messaging with IP addressing that permits each device (wireless and wired) to transmit and receive double messages simultaneously, resulting in seamless data transfer during equipment failures
- Reliable system operation trains keep moving in the system if portions of the equipment fail
- Proven wayside, vehicle, and central office designs use of proven design techniques for high reliability and availability
- ATS architecture derived from years of experience being the industry leader in computerized central offices

System Safety Program Plan (SSPP) was implemented from the planning stages of the CBTC system and will continue throughout the project's life cycle. The SSPP describes all essential activities that are performed to show that the system meets or exceeds the specified qualitative and quantitative safety requirements

Technologies	Solution	Supplier	Applications
Cab signal SSO	EATC	Alstom	Sonoma-Marin Area Rail Transit (SMART), Portland and west Railroad (PNWR)
Balise SSO	ACSES	Alstom/PHW Bombardier/Siemens	Amtrak's NEC, MBTA, SEPTA, Metro-North, LIRR, NY MTA
Balise SSO	ASES	Ansaldo/Hitachi STS	NJT
Balise SSO	Trainguard MT ITC	Siemens	
Balise SSO	PZB2X2	BBR	Metro Bursa, Edmonton Valle LRT, Boston Green Line
CBTC SSO	I-ETMS	Wabtec	Alaska Railroad, BNSF. CSX, Norfolk Southern (NS), UPRR, Caltrain, LA Metrolink, Denver RTD
Satellite SSO	ITCS	GETS/Alstom	Amtrak's Michigan line, China Qinghai-Tibet
Satellite SSO	Trainguard Sentinel	Siemens	Panama Canal Railway, Tasmania Railway, Mozambique-Nacala Railway

CBTC w/ moving block	SelTrac	Thales	Vancouver SkyTrain, People Mover, London Docklands LRT, HK MRT, Las Vegas Monorail, Wuhan Metro, Beijing Subway, Shanghai Metro, Washington Reagan Airport, Guangzhou Metro, London Underground, Busan Metro, Dubai Metro, Istanbul Metro, Paris Metro, Edmonton LRT, Salvador Metro, Nanjing Metro, Shinbundang Line, Shenzhen Metro, Hyderabad Metro, NYC Subway, Kuala Lumpur Metro, Walt Disney World Monorail, Singapore MRT, Doha Metro, Ottawa LRT, Sao Paulo Metro, Tokyo,
CBTC w/ moving block	CITYFLO	Bombardier/Alsto m	Bangkok Skytrain, Istanbul Metro, SFO Airport Seattle-Tacoma Airport, Dallas Airport, London Heathrow Airport, Madrid Metro, Las Vegas Airport, Taipei Metro, Guangzhou Metro, London Gatwick Airport, Philadelphia SEPTA, Sacramento Airport, Shenzhen Metro, Soul Metro, Phoenix Airport, Riyadh, Tenjin Metro, Jeddah Airport, Munich Airport, San Paulo Metro, Delhi Metro, Bangkok MRT, Kuala Lumpur Metro, Bangkok MRT
CBTC w/ moving block	Urbalis	Alstom	Sao Paulo Metro, Milan Metro, Mexico Metro, Santiago Metro, Malaga Metro, Dubai LRT, Panama Metro, Amsterdam Metro, Chengdu Metro, Wuxi Metro, Lille Metro, Lucknow Metro, Taichung Metro, Riyadh Metro, Singapore MRT, Lausanne Metro, Toronto subway, HK MRT, Kochi Metro, Sydney Metro, Shenzhen Metro, Guangzhou Metro, Kunming Metro, Wuhan Metro, Ningbo Metro, Beijing Subway
CBTC w/ moving block	Trainguard MT	Siemens	Barcelona Metro, NYC Subway, San Paulo Metro, Paris Metro, Algiers Metro, Chongqing Metro, Beijing Subway, Budapest Metro, Helsinki Metro, Xian Metro, Nanjing Metro, Buenos Aires, Fuzhou Metro, Copenhagen, Houston, Rennes, Gyeonggi, Bangkok MRT, Suvarnabhumi Airport, HK MRT, Guangzhou Metro
CBTC w/ moving block	CBTC	Ansaldo/Hitachi Rail STS	Shenyang Metro, Xian Metro, Ankara Metro, Taipei Metro, Stockholm Metro, BART
CBTC w/ moving block	Sirus	Invensys/Siemens	Madrid Metro, San Paulo Commuter, Caracas Metro, Singapore MRT, Marmaray

Table 3 - List of SSO/CBTC Equipment Suppliers and Applications

HNTB

Ultra-Wideband (UWB) Train Positioning in CBTC

CBTC relies on continuous updating of train locations. Positioning methods include track circuits, balise or transponders, tachometers, odometry methods, and global navigation satellite systems (GNSS). The latest development has UWB applications.

Companies investing in UWB technology face challenges such as interoperability with competing vendors and adapting to unique protocols adopted by various agencies. Additionally, UWB systems must be safety certified before they can be deployed in revenue service. Notwithstanding these hurdles, UWB provides benefits that encourage many transportation agencies to consider the technology as part of their system enhancements.

How it Works

UWB uses narrow radio frequency pulses to wirelessly communicate between the train and small devices installed on the wayside. Using a method known as Time-of-Flight to measure the time it takes for signals to be sent and received, the distance between the radios can be instantly captured. As the train moves along the track, an onboard computer calculates its exact position 10-15 times each second with exceptional accuracy and reliability.

Ultra-Wideband Application in Signaling

UWB technology determines the location of vehicles with unmatched positional certainty. The system is like a blanket of radio coverage over the subway lines virtually surrounding the tracks with smart sensors that pinpoint train location down to a few inches. To date, UWB programs initiated within the transportation industry have focused on assessing technology's reliability, interoperability, and safety certifiability. Because UWB equipment is installed on the wayside and in the interior control cabinets on the train (as opposed to the track bed and the undercarriage of the rolling stock), the positioning systems required to manage train headways can be deployed faster, at lower cost, and with minimal disruption. For transportation agencies or railroads who are installing CBTC, Positive Train Control (PTC) systems, or performing midlife enhancements to existing systems, UWB offers several valuable benefits, including:

- **Increasing System Throughput**: Ultra-precise positioning improves headways, allowing trains to run closer together and more frequently. The result is an increased capacity that improves on-time performance and overall customer service.
- **Improving Maintenance, Increasing Performance, and Reducing Cost**: UWB equipment is installed along the wayside, not in the track bed, making installations safer, faster, and easier to maintain with greater reliability for riders. By using wayside equipment, UWB

technology can also be more affordable to install since it builds off the existing infrastructure instead of requiring new locations for installation, power, and connectivity. In cases where CBTC has been integrated with UWB, UWB technology has proven to accelerate the installation times and performance of CBTC systems. This integrated approach can reduce the delays often associated with retrofitting existing rail lines (brownfield installations) and improve the system's overall reliability.

- **Providing a Vital Positioning Subsystem**: Like many systems around the United States are reliant on GPS and wheel tachometers for localization and odometry functions, many railroads are finding that wheel slips, underground operations, and navigating through dense city environments often proves too challenging for the systems of today to handle. Integrating UWB into existing systems would allow the systems of today to improve the railroad's operational efficiency and improve its operations' safety by decreasing instances of delocalization.

The innovative new application of UWB technology has the potential to profoundly improve the life of commuters, especially as urban populations are expected to grow exponentially in the coming decades. Incorporating new technologies like UWB into existing and new signaling equipment, urban transit agencies will be able to meet the challenges of rail systems' expansion directly, improving the customer experience while helping reduce overall cost.

There are some locations currently using this, or similar, technology. Vendors are unifying collision avoidance and worker protection under a single solution, and it is reportedly being deployed for MBTA in Boston and some freight rail systems. Port Authority of NY/NJ Exclusive Bus Lane (XBL) Automated Bus Project is beginning to automate buses in the Lincoln Tunnel using the same technology to increase current capacity/improve safety. The CV/UWB technology is a vital component of this project. NYCDOT CV Pilot project showed five-centimeter accuracy with key enabling UWB was possible in the urban canyon environment where GPS wasn't available. NYC Transit tested the technology for deployment on the subway trains and right-of-way and awarded the idea for the area of the signal of the MTA Challenge. MTA has reportedly implemented the first phase of deployment of this technology. It offers the advantage of using standards-based technologies instead of proprietary solutions and boasts many benefits to rail signaling, passenger communications, and right-of-way safety. It will also provide a lower implementation cost than existing signaling systems.

Case Study: NYTC UWB Based Train Control System Pilot Program

In March 2019, NYCT awarded Thales, in partnership with Piper, a contract for a UWB-based Train Control System Pilot Program on the 7 line. At the same time, NYCT awarded Siemens with Humatics a contract for a UWB-based Train Control System Pilot Program on the Canarsie L line.

Figure 25 - UWB Installation on Track Side Mounting Poles[19]

The scope of the pilot was to prepare the new platform for safety certifiability, and it consisted of nine months of testing and collecting 2,500 hours of operational data. As part of the pilot program, four trains on the 7 line, which is one of two lines in the system already equipped with CBTC, have been outfitted with the Thales' CBTC system that integrates Piper's UWB technology. Four trains on the Canarsie line were outfitted with Siemens' CBTC system that integrates Humatics UWB technology.

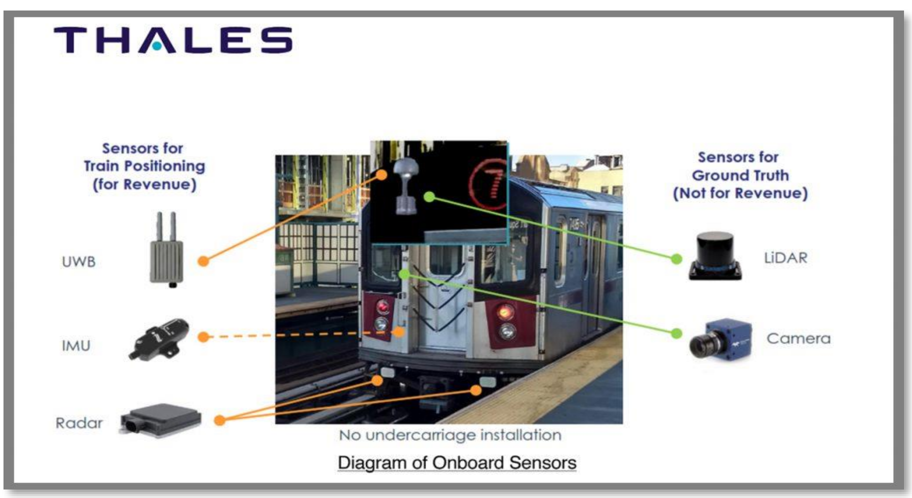

Figure 26 - UWB and Onboard Sensors[20]

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[19] Source: MTA

[20] Source: Thales

The successful results of a nine-month pilot of ultra-wideband (UWB) technology have been demonstrated by the New York City Transit Metropolitan Transportation Authority (MTA) on the Flushing 7 and Canarsie L lines, modernizing the agency's signaling system and delivering safer, faster, and more reliable service. The nine-month pilot program with strong results demonstrated the potential for UWB positioning technologies to integrate seamlessly with Communications-Based Train Control (CBTC) to improve system reliability and the speed of delivery for upgraded signaling systems.

The Thales/Piper UWB system employs five conveniently located onboard sensors. There is no undercarriage equipment.

There are five high-tech components/sensors integrated with Thales' NGP systems:

- UWB, a type of radio communication that uses a very low amount of energy with short-range, high-bandwidth waves employing a wide range of the radio spectrum. NYCT's Flushing Line system uses Piper onboard UWB radios and controllers and Piper UWB wayside "anchors." The NGP system uses UWB to receive location updates every 100 milliseconds.
- IMUs (Inertial Measurement Units) detect changes in speed and direction with an "extraordinary" level of accuracy. The NGP system uses the IMU for inertial navigation and orientation verification.
- Radar, Camera, and Camera are used as train collision prevention subsystems.

Key Advantages and Features of UWB:

Rapid implementation is achieved through a reduction of onboard equipment by elimination of vehicle undercarriage installation.

Improved train positioning accuracy, called NGP (Next-Generation Positioning), is achieved through modern onboard sensors, including UWB radios. The UWB test runs are used to evaluate the accuracy and fault tolerance of the NGP system. Each end-of-the-test train is equipped with a Thales Vehicle on Board Computer (VOBC), part of the CBTC system, integrated with the NGP sensors.

Accelerated start-up position initialization: The NGP system is described as "highly tolerant of equipment or sensor failures without impacting overall function." Upon power-up and initialization, the NGP system tells the onboard controller precisely where it is located, enabling a train to initialize and engage Automatic Train Operation (ATO) faster than current-generation CBTC systems.

High accuracy and availability: NGP provides greater positional accuracy and can support much greater separation between wayside landmarks. This means that future CBTC systems based on this technology will support more precise station stopping accuracy and will be able to travel a greater distance between wayside landmarks. If inputs from sensors or UWB controllers at one end of the train fail, the system can seamlessly switch over to inputs from the other end of the train.

Case Study: Humatics' Rail Navigation System

Humatics' Rail Navigation System is a drop-in replacement for traditional odometry sensors such as tachometers, transponders, and doppler radars. Humatics' systems consist of industrial-grade ultra-wideband (UWB) beacons and Inertial Measurement Units (IMU) providing position, speed, and acceleration to vital and non-vital car-borne systems for signaling, train control, train management, and passenger information.

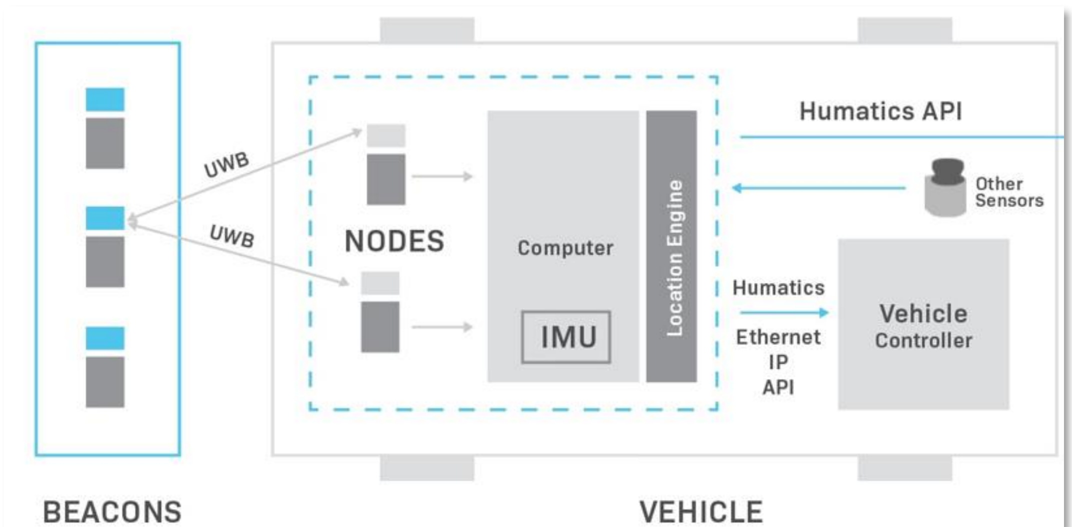

Figure 27 - Humatics UWB System Architecture[21]

Humatics' Rail Navigation System operates similarly to satellite positioning serving as "terrestrial satellites" and works by continually ranging from car-borne beacons to a constellation of UWB beacons. Given this architecture, UWB ranging is especially well-suited to augment GNSS positioning on track sections with poor or no signal reception, such as urban canyons and tunnels.

Through its high availability and ultra-precise UWB localization network, Humatics enables safety-critical train positioning in all conditions, unlocking various applications, including automatic train operations, platooning, advanced driver assistance, platform door control, roadway worker safety, and emergency location services.

[21] Source: Humatics

System Architecture

Humatics' Rail Navigation System has a simple architecture allowing installation within any vehicle and on any track, interfacing into vehicle controllers and systems that depend on safety-critical positioning information: CBTC, ERTMS/ETCS, PTC, TCMS, PA/CIS, CAD/AVL, etc.

Applications

Signaling & Train Control: Replace legacy odometry systems such as wheel sensors and track-mounted transponders. Interfaces with Communication-Based Train Control (CBTC), European Train Control System (ETCS/ERTMS), Positive Train Control (PTC), and transit CAD/AVL systems.

Driver Assistance Systems: Integrate with the onboard Train Control & Management System (TCMS) and Driver Machine Interface (DMI) to provide situational awareness and enable precision stops at platforms. Provide zero-speed signal and train type information to SIL-4 door controllers.

Automatic Train Operation (ATO): Train-to-train UWB ranging provides the ultra-precise high-frequency relative positioning information necessary for vehicle platooning. In addition, train-to-train UWB communication enables the synchronization of braking and traction between trainsets.

Hi-Rail Vehicles and Roadway Worker Protection UWB: provide the ranging and communication infrastructure for roadway worker protection systems. The positioning precision allows for making the safety-critical distinction between workers and vehicles on and off the tracks.

Yard and Depot Management: Track buses and railcars in yards and indoor maintenance facilities. Humatics industry-leading 1600m ranging distance and robustness to interference means large depots require fewer UWB beacons to achieve precise vehicle positioning.

Benefits

- Alternative to GNSS in tunnels, stations, depots, and urban canyons
- Precise sub-5cm safety-critical positioning in all weather conditions
- Longest-ranging ultra-wideband radio technology on the market

Alternative Technologies Evaluations

Alternative Technologies Evaluations criteria and scoring:

Criteria	Weightings
1. SSO Function Ability to support civil speed compliance Ability to support Red signal compliance Ability to allow localized speed reduction for roadway worker safety and track protection Adherence to signal safety standards concerning SSO system design principles	30%
2. Civil Speed enforcement in non-signal territory	10%
3. Efficiency/throughput of the system	10%
4. Redundancy of system	10%
5. Support for robust LRT fallback operations in the event of SSO outages or failures	10%
6. Vehicle interface and retrofit design considerations	10%
7. Integration to existing LRT signal system considerations	10%
8. Future proof/upgrades within two decades of operation	10%

Table 4 - Alternative Technologies Evaluation Criteria and Weightings

The scoring worksheet developed for this evaluation breaks each of these metrics down into one to eight criteria. It is intended that the requirements can be easily scored. Scores are 0 to 10, with ten being the highest (most favorable). The total score for each technology is the total weighted score for each of the eight criteria.

Criteria	Weight	Technologies							
		Cab Sig SSO		Balise SSO		CBTC SSO		CBTC Moving Block	
		Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score
1. SSO Function	30%	100	30	100	30	100	30	100	30
2. Civil Speed enforcement in non-signal territory	10%	0	0	90	9	70	7	70	7

Criteria	Weight	Technologies							
		Cab Sig SSO		Balise SSO		CBTC SSO		CBTC Moving Block	
		Score	Wt. Score	Score	Wt. Score	Score	Wt. Score	Score	Wt. Score
3. Efficiency/ throughput of system	10%	10	1	30	3	40	4	80	8
4. Redundancy of system	10%	0	0	80	8	70	7	70	7
5. Support for robust LRT fallback operations	10%	90	9	80	8	70	7	70	7
6. Vehicle interface and retrofit design considerations	10%	90	9	70	6	60	7	50	7
7. Integration to existing LRT signal system considerations	10%	70	8	70	6	60	7	50	6
8. Future proof /upgrades within two decades of operation	10%	70	6	70	6	70	8	80	8
Weighted Total for Each Technology			63		76		77		80

Table 5 - Scoring of Alternative SSO/CBTC Technologies

Evaluations to E-ATC Cab Signal SSO

1. SSO Functions:

- Ability to support civil speed compliance: comply
- Ability to support Red signal compliance and allow localized speed reduction for roadway worker safety and track protection: comply
- Adherence to signal safety standards concerning SSO system design principles: comply

2. Ability to support civil speed compliance in the non-signaled territory

This technology does not support this function

3. Efficiency/throughput of the system

In general, an overly conservative SSO system may slow trains below the level human engineers had safely operated them. Railway speeds are calculated with a safety factor such that slight excesses in speed will not result in an accident. SSO system might be unable to account for variations in weather conditions or train handling and might have to assume a worst-case scenario, further decreasing performance.

On the positive side, the SSO will prevent a train overruns a red signal; as such, the overlap circuit/distance in ABS is no longer needed. The RTD LRT overlap circuit length is about 593' at the 35-mph zone and 1128' at the 55-mph zone. In theory, the headway can be reduced by 12 seconds at the 35-mph zone and by 14 seconds at the 55-mph zone at some signal locations. The reduced headway will be beneficial for the corridor where a tight headway is required.

4. Redundancy of system

The existing wayside signal processor and onboard UltraCab II will be upgraded for the cab signal system upgrade, and the current system has no redundancy.

The score of this evaluation item is low.

5. Support for robust LRT fallback operations in the event of SSO outages or failures.

A safe and prudent symmetry ensures trains can continue moving while minimizing the risk of trains operating under a degraded mode of a train control system.

Since the ABS system will co-exist with the cab signal-based SSO overlay system as an underlying system, the wayside signals system will be used as a fallback system in the event of onboard E-ATC failure. The train will default to its most restrictive authority, such as a Stop or stop-and-proceed. An operator will contact OCC, cut out the onboard SSO, and use the wayside signal system to continue the operation. The score of his evaluation item is high.

6. Vehicle interface and retrofit design considerations:

- The existing onboard ATS system will be upgraded to the full Cab Signal system by upgrading the onboard UltraCab II equipment
- New Odometers will be installed
- The existing onboard cab code antenna can be reused. A display unit will be added to each cab
- Change is relatively simple

the score of this evaluation item is the highest among all technologies.

7. Integration to existing LRT signal system considerations:

- The existing wayside and onboard signal equipment will be reused with some upgrades
- On the negative side, the signal control line drawing will need to be redesigned to include the new cab signal speed codes
- New Audio Frequency Overlay (AFO) track circuits may be needed to obtain optimal speed control

8. Future proof or likelihood for major upgrades within two decades of operation

The existing ElectrologIXS & VHLC based signal equipment is reusable. The aged existing VHLC units can be replaced by newer ElectrologIXS units if needed, as the ElectrologIXS system is widely used in the US market. It is expected that the equipment supplier Alstom will provide continuous support on the product in the next two decades.

Evaluations to Balise Based SSO

1. SSO Functions:

- Ability to support civil speed compliance: comply
- Ability to support Red signal compliance and allow localized speed reduction for roadway worker safety and track protection: comply
- Adherence to signal safety standards concerning SSO system design principles: comply

This technology meets SSO requirements. The score of this evaluation item is high.

2. Ability to support civil speed compliance in the non-signaled territory:

- This technology can support this function
- Radio communication is not required
- The score of his evaluation item is the highest among all technologies.

3. Efficiency/throughput of the system

In general, an overly conservative SSO system may slow trains below the level operators can safely operate them. Railway speeds are calculated with a safety factor such that slight excesses in speed will not result in an accident. SSO system might be unable to account for variations in weather conditions or train handling and might have to assume a worst-case scenario, further decreasing performance.

On the positive side, the SSO will prevent a train overruns a red signal; as such, the overlap circuit/distance in ABS is no longer needed. The RTD LRT overlap circuit length is about 593' at the 35-mph zone and 1128' at the 55-mph zone. In theory, the headway can be reduced by 12 seconds at the 35-mph zone and by 14 seconds at the 55-mph zone at some signal locations. The reduced headway will be beneficial for the corridor where a tight headway is required.

4. Redundancy of system

Transponder sets can be installed to improve reliability. The control unit can be configured to provide redundancy. Due to physical constraints on the train, it may be difficult to duplicate the entire complement of onboard SSO equipment fully. For example, there is not sufficient space to install duplicate transponder interrogator antennae or inductive pick-ups at each end of the car.

Radio Systems Architecture: The loss of a Wayside Communication manager (WCM), for example, due to a power outage or lightning strikes, results in a standby WCM taking over the communications duties between Base Communication Manager (BCM) and the office systems. Because a locomotive's radio can be heard by a number of BCMs, the WCM examines the indication RF signal strength of each BCM that heard the locomotive to determine the strongest talk path back to the locomotive is. The WCM maintains a record of three possible talk paths to the locomotive. The strongest path is always selected if the office needs to communicate back to the locomotive as a locomotive moves from region to region. The radio signal strengths recorded by BCMs get conveyed to the WCMs change. BCMs that fall out of locomotives range are removed from talk path routes within the WCM in favor of the BCMs that are coming into range. In this way, the WCM is constantly aware of where each locomotive is located, and which talk path is best used to communicate with the locomotive. Such information is also conveyed to the office so that office systems may make use of it. Another aspect of redundancy is the system design that looks forward along the track, acquiring TSRs for the future if a temporary communications failure occurs. Since each locomotive has TSRs for at least three future segments of the rail line, the locomotive has TSR information for the "dark" segment already before it proceeds into the dark segment.

5. Support for robust LRT fallback operations in the event of SSO outages or failures

A safe and prudent symmetry ensures trains can continue moving while minimizing the risk of trains operating under a degraded mode of a train control system.

Since the ABS system will co-exist with the Balise-based SSO system as an underlying system, the wayside signals system will be used as a fallback system in an onboard SSO equipment failure or wayside Balise failure. The train will default to its most restrictive authority: Stop or stop-and-proceed. The operator will contact OCC, cut out the onboard SSO, and use the wayside signal system to continue the operation.

6. Vehicle interface and retrofit design considerations

New onboard Balise reception antenna, processer, odometers, and driver display units will be installed on each end of the train. The radio unit will be used to communicate worker protection functions. The track database will be gathered and loaded into the processor. Change is complex.

7. Integration to existing LRT signal system considerations

The Balise technology is new to the RTD LRT system, and integration to the existing signal system will require careful planning. The current ABS system can remain in service with some modifications.

8. Future proof or likelihood for major upgrades within two decades of operation

The Balise SSO system has been installed in many rail applications in the US and European rail systems. It is expected that the technology will remain in service for the next two decades in the world market. The selection of system supplier should be carefully planned to ensure that the latest system is selected will be done in a manageable manner.

Evaluations to CBTC Based SSO

1. SSO Functions:

- Ability to support civil speed compliance: comply
- Ability to support red signal compliance and allow localized speed reduction for roadway worker safety and track protection: comply
- Adherence to signal safety standards concerning SSO system design principles: comply

This technology meets all SSO requirements. The score of his evaluation item is high.

2. Ability to support civil speed compliance in the non-signaled territory

This technology can support this function. This technology requires onboard radio communication and GPS.

3. Efficiency/throughput of the system

In general, an overly conservative SSO system may slow trains below the level operators can safely operate on them. Railway speeds are calculated with a safety factor such that slight excesses in speed will not result in an accident. SSO system might be unable to account for variations in weather conditions or train handling and might have to assume a worst-case scenario, further decreasing performance.

On the positive side, the SSO will prevent train overruns of a red signal; as such, the overlap circuit/distance in ABS is no longer needed. The RTD LRT overlap circuit length is about 593' at the 35-mph zone and 1128' at the 55-mph zone. In theory, it is possible that the headway can be reduced by 12 seconds at the 35-mph zone and by 14 seconds at the 55-mph zone at some signal locations. The reduced headway will be beneficial for the corridor where a tight headway is required.

4. Redundancy of system

The vital train control subsystem is usually configured to be a dual redundant hot-standby equipped system. The non-vital subsystem such as communications and back-office can be configured to provide adequate redundancy as needed. Due to physical constraints on the train, it may be difficult to duplicate the entire complement of onboard SSO equipment fully. For example, there is not sufficient space to install duplicate transponder interrogator antennae or inductive pick-ups at each end of the car.

Radio Systems Architecture: The loss of a Wayside Communication Manager (WCM), for example, due to a power outage or lightning strike, results in a standby WCM taking over the communications duties between BCM and the office systems. Because a locomotive's radio can be heard by a number of BCMs, the WCM examines the indication RF signal strength of each BCM that heard the locomotive to determine the strongest talk path back to the locomotive. The WCM maintains a record of three possible talk paths to the locomotive. The strongest path is always selected if the office needs to communicate back to the locomotive as a locomotive moves from region to region. The radio signal strengths recorded by BCMs get conveyed to the WCMs change. BCMs that fall out of locomotives range are removed from talk path routes within the WCM in favor of the BCMs that are coming into range. In this way, the WCM is constantly aware of where each locomotive is located, and which talk path is best used to communicate with the locomotive. Such information is also conveyed to the office so that office systems may make use of it. Another aspect of redundancy is the system design that looks forward along the track, acquiring TSRs for the future if a temporary communications failure occurs. Since each locomotive has TSRs for at least three future segments of the rail line, in the event there is a segment of the track which for some reason has lost radio communication to the office; the locomotive has TSR information for the "dark" segment already before it proceeds into the dark segment.

5. Support for robust LRT fallback operations in the event of SSO outages or failures

Since the ABS system will co-exist with the CBTC based SSO overlay system as an underlying system, the wayside signals system will be used as a fallback system in an onboard SSO equipment failure or wayside communication system failure. The train will default to its most restrictive authority: Stop or stop-and-proceed. The operator will contact OCC, cut out the onboard SSO, and use the wayside signal system to continue the operation.

6. Vehicle interface and retrofit design considerations:

- New onboard radios
- GPS receivers
- Odometer, processor, and driver display unit will be installed on each end of the car

- The track database will be gathered and loaded into the processor

Change is complex.

7. Integration to existing LRT signal system considerations

This technology is new to RTD LRT system, and integration to the existing signal system will require careful planning. This technology requires a new radio system and a new back office, and implementation can be complex. On the positive side, since this technology is currently used in RTD Commuter lines, RTD can use its experience to reduce the risk during LRT implementations.

8. Future proof or likelihood for major upgrades within two decades of operation

The CBTC based SSO system has been installed in many rail applications in the US. It is expected that today's technology will remain in service for at least the next two decades while new technology continues to develop. Selection of supplier and system should be carefully planned to ensure the latest system is selected, and if necessary, a system upgrade will be done in a manageable manner.

Evaluations to CBTC Moving Block

1. SSO Functions:

- Ability to support civil speed compliance: comply
- Ability to support Red signal compliance and allow localized speed reduction for roadway worker safety and track protection: comply
- Adherence to signal safety standards for SSO system design principles: comply

Most CBTC systems meet European Train Control System (ETCS) Level 2 or 3 standards.

2. Ability to support civil speed compliance in the non-signaled territory

This technology can support this function. This technology requires onboard radio communication and GPS.

3. Efficiency/throughput of the system

The CBTC moving block technology has the benefit of improving the headway and throughput of the system. This technology has the highest score on this evaluation item among all technologies.

4. Redundancy of systems

The vital train control subsystem is usually configured to be a dual redundant hot-standby equipped system. The non-vital subsystem such as communications and back-office can be configured to provide adequate redundancy as needed. Due to physical constraints on a train, it may be difficult to fully duplicate the entire complement of onboard SSO equipment. For example, there is not sufficient space to install duplicate transponder interrogator antennae or inductive pick-ups at each end of the car.

Radio Systems Architecture: The loss of a WCM, for example, due to a power outage or a lightning strike, results in a standby WCM taking over the communications duties between BCM and the office systems. Because a locomotive's radio can be heard by a number of BCMs, the WCM examines the RF signal strength of each BCM of the locomotive to determine the strongest talk path back to the locomotive is. The WCM maintains a record of three possible talk paths to the locomotive. The strongest path is always selected if the office needs to communicate back to the locomotive as a locomotive moves from region to region. The radio signal strengths recorded by BCMs get conveyed to the WCMs change. BCMs that fall out of locomotives range are removed from talk path routes within the WCM in favor of the BCMs that are coming into range. In this way, the WCM is constantly aware of where each locomotive is located, and which talk path is best used to communicate with the locomotive. Such information is also conveyed to the office so that office systems may make use of it. Another redundancy aspect is the system design that looks forward along the track, acquiring TSRs for the future if a temporary communications failure occurs. Since each locomotive has TSRs for at least three future segments of the rail line, in the event there is a segment of the track which for some reason has lost radio communication to the office; the locomotive has TSR information for the "dark" segment already before it proceeds into the dark segment.

5. Support for robust LRT fallback operations in the event of SSO outages or failures

The primary risk of an electronic train control system is that if the communications link between any trains is disrupted, all or part of the system might have to enter a failsafe state until the problem is remedied.

The existing ABS system will be reconfigured as an underlying system consisting of track circuits and wayside signals at the interlocking. In the event of an SSO failure, the train will default to its most restrictive authority: Stop or stop-and-proceed. The operator will contact OCC and cut out the onboard SSO. A manual block or station to station operation can be implemented with an underlying system of track circuits and interlocking signals.

6. Vehicle interface and retrofit design considerations:

- New onboard radio
- GPS receiver

- onboard computer, and driver display unit will be installed on each end of the car
- The track database will be gathered and uploaded to the processor

Change is complex.

7. Integration to existing LRT signal system considerations

This technology is new to RTD LRT system, and integration to the existing signal system will require careful planning. This technology requires a new radio system and a new back office. Implementation can be complex. Due to the complexity in implementation, the score of this evaluation item is the lowest among all technologies.

8. Future proof or likelihood for major upgrades within two decades of operation

The CBTC system has been installed in many rail applications worldwide, especially in European rail systems. Today's technology will remain in service for at least the next two decades while new technology continues to develop. Selection of supplier and system should be carefully planned to ensure the latest system is selected and, if necessary, a system upgrade will be implemented in a manageable manner.

SSO/CBTC Implementations

The implementation analyses are also included in this study and are detailed in:

- Modifications and integrations to existing LRT signal system
- Proof-of-concept testing
- Phasing of design and installation of system upgrades
- Rough time estimation and schedule of design and installation
- Rough cost estimation of design and installation.

Existing System Modifications and New Installations

Cab Signal Based SSO

Block Design and Route & Aspect charts:

- **Block boundaries**: although changing block boundaries may benefit cab speed code optimization, construction will be complex. Change is not recommended.
- **ABS Signal control**: If desirable, the overlap circuit/double red layouts can be changed to a single red/no overlap layout.
- **Speed Cab code & Maximum Allowable Speed**: Permanent Speed Limit will be added to the charts. New speed codes control lines will be redesigned to replace the existing ATS cab codes. Software time delay logic to delay the "downgrade" of cab codes transmitted by the wayside cab code generator to each train as it enters a block. Block designers will use these time-delayed reductions in enforced speed to optimize travel time through each block while still providing braking distance for safe enforcement of speed restrictions. In addition, an AFO track circuit may be added at the approach and end of the civil speed limit to provide speed code optimization.

Interlocking and Intermediate relay houses: most existing equipment will remain with no significant changes. The software cab generator will be upgraded to provide full-speed codes to replace the current go/no-go cab codes.

Wayside installations: new AFO track circuit may be added for civil speed limit approach/end detection.

Crossing relay houses: no change.

Communication system: no change.

Operation Control Center (OCC): additional Control Office hardware and software will be installed at OCC to apply and remove TSR, including work zones and MDs for highway-rail crossings.

Onboard signal equipment: the existing onboard ATS system will replace the new Cab signal ATP system with interface to train propulsion and braking systems. Existing onboard UltraCab II equipment will be upgraded to provide detection of new speed codes. A new display unit will be added to each cab of the train. New odometers will be added. The existing ATS will be removed.

Balise Based SSO

Block Design and Route & Aspect charts:

- Block boundaries: no change.
- ABS Signal control: If desirable, the overlap circuit/double red layouts can be changed to a single red/no-overlap layout.
- ATS Cab signal code: the existing ATS system can remain or be removed.
- Balise: location of balise and other information will be added as needed.

Interlocking and Intermediate relay houses: add interface and Lineside Encoder Unit (LEU) for the new balise system.

Wayside installations: add new Balise devices on track at desirable locations.

Crossing relay houses: no change.

Communication system: optional data radio can be installed at the wayside signal location to transmit signal status to train. An optional data radio system can be installed to provide temporary speed restriction and absolution stop information to the train. Alternatively, the TSR function can also be provided by installing a temporary balise at the work zone without radio system support.

Operation Control Center: Additional control office hardware and software will be installed at the OCC to provide train management functions, such as applying and removing TSRs, including work zones and MDs for highway-rail crossings.

Onboard signal equipment: The new onboard equipment consists of a computer that stores the route characteristics database, a distance measurement subsystem to track train position, an antenna subsystem for the track-mounted balise, and an optional data radio subsystem for communication with wayside and OCC systems. The operator has a consolidated display displaying the train's target speed and other useful operating information in the cab. The existing ATS system can either remain, be disabled, or be removed.

CBTC Based SSO

Block Design and Route & Aspect charts:

- Block boundaries: no change.
- ABS Signal control: If desirable, the overlap circuit/double red layouts can be changed to a single red/no overlap layout.
- ATS Cab signal code: the existing ATS system can remain or be removed.

Interlocking and Intermediate relay houses: add interface equipment such as a WIU

Wayside signal installations: no change.

Crossing relay houses: no change, the Wireless Crossing activation system installed in RTD Commuter Rail system will not be installed in RTD LRT system.

Communication system: add new data radio system to provide continuous coverage through the entire corridors, require power and fiber network connections for each radio location. The data radio system will be licensed from FCC's Wireless Telecommunications Bureau.

Operation Control Center: additional control office hardware and software will be installed at OCC to provide BOS functions.

Onboard signal equipment: The new onboard equipment consists of a computer that stores the route characteristics database, a distance measurement subsystem to track train position, a GPS receiver for train location tracking, and a data radio subsystem for communication with BOS and relay houses. The GPS receivers should support a sufficient number and type of sensors to overcome any negative environment influences (tall buildings and obstacles that prevent a clear view of the sky,) as well as the ability to overcome the effects of GPS satellite shadowing and multipath errors that could affect navigation accuracy to the extent that the required system availability could not be met. The driver has a consolidated display in the cab that displays the train's target speed and other useful operating information. The existing ATS system can either remain, be disabled, or be removed.

CBTC Moving Block

This system could be overlaid on top of and co-exist with the existing fixed-block train control up until the CBTC system cutover with minimal interruption.

<u>Block Design and Route & Aspect charts:</u>

- Block boundaries: no change.
- ABS Signal control: the ABS will be disabled when CBTC is active and in control.
- ATS Cab signal code: the existing ATS system will be removed.

Interlocking and Intermediate relay houses: add interface equipment such as a WIU.

Wayside signal installations: intermediate signals will be removed.

Crossing relay houses: no change.

Communication system: add new data radio system to provide continuous coverage through the entire corridors, require power and fiber network connections for each radio location. The data radio system will be licensed from FCC's Wireless Telecommunications Bureau.

Operation Control Center: additional control office hardware and software will be installed at OCC to provide BOS function.

Onboard signal equipment: The new onboard equipment consists of a computer that stores the route characteristics database, a distance measurement subsystem to track train position, a GPS receiver for train location tracking, and a data radio subsystem for communication with the BOS and relay houses. The GPS receivers should support a sufficient number and type of sensors to overcome any negative environment influences (tall buildings and obstacles that prevent a clear view of the sky,) as well as the ability to overcome the effects of GPS satellite shadowing and multipath errors that could affect navigation accuracy to the extent that the required system availability could not be met. The driver has a consolidated display in the cab that displays the train's target speed and other useful operating information. The existing ATS system will be removed.

Proof of Concept Testing

A proof-of-concept phase should be specified to manage the risk against design, technology, installation, and reliability issues. The first step is to select proposer(s) who have already passed the initial screening process. The selected proposer(s) will install its system on a test track and test vehicle to demonstrate the proposed method. By requiring milestones for proof of concept and comparing the test results of each proposer's system, RTD will retain the ability to accept or terminate the project before fully committing the funding and resources. The following items should be considered in scoring this proof of concept:

- Determine if vital wayside systems can be safety certified
- Determine if wayside systems are reliable
- Determine if vital vehicle systems and interfaces can be safety certified
- Determine if vehicle systems are reliable
- Determine that wayside/vehicle interfaces are reliable
- Determine that control center interfaces are functional and reliable
- Determine that the SSO system functions safely and reliable as a whole
- Demonstrate that the proposed system can be integrated into the existing system with no issues
- Demonstrate the efficiency/throughput of the system is acceptable

The testing would take place at night with no passengers or during operating hours with rules for the present signal system in effect. The Proof-of-Concept operation testing should provide the basis of technology selection, lessons for implementing the rest of the system, and training insights for both operations and maintenance personnel. The main concern is not so much the installed equipment on the wayside but the interaction of the vehicles with the SSO systems over an extended section of track. It would be advantageous to identify any vehicle SSO interface issues early in the installation process. A proof-of-concept operation should identify any harmonic EMI issues.

It is proposed that the SW corridor tracks between Elati Yard and Mineral Station be used for proof-of-concept testing. The Elati Yard South interlocking will be used for train turnaround on the north end of the test track, and Mineral interlocking will be used for train turn around on the south of the test track. One test train will be modified to equip with onboard SSO equipment. The Elati Yard will be used for test train retrofit and retrofit of Control Center. For a CBTC system, the following equipment will be installed:

- Positioning transponders (if used),
- Wayside radio units,
- A set of backbone and security communications equipment, and
- A computer system will simulate the wayside equipment and provide for communications and delivery of movement authority to the onboard controller.

Construction Phasing

For an extensive system such as RTD LRT, the SSO system should be implemented and be cut over in phases, rather than the total system being cut over at one time. The gradual implementation of the SSO system would provide RTD with a higher level of confidence before implementing the system in entire corridors. Since the existing plan must remain in operation during construction with minimal impact, the implementation would commence at less busy branch line(s) and proceed toward the busy CPV and CC corridors. In this manner, the contractor and RTD can work out many of the initial “bugs” in the system in locations with easy access and less existing traffic. The SSO implementations will be carefully planned that both the “SSO equipped” and “non-equipped” LRV will be fully protected when moving in and out of different corridors.

Assuming that the SSO system will be installed and tested on the vehicles at the Elati Yard, the logical implementation sequence would be to implement the first SSO system in the SW line. The introduction of service on the SW Branch provides an ideal testbed for the installed SSO system before implementing the system in other corridors. The “proof of concept” segment will be first installed between Elati Yard and Mineral Station and be used to test the “SSO equipped” LRV fleet.

When RTD is satisfied with SSO operations on the SW line, the commissioning effort will proceed into the other corridors, for example: to SE line, to CC line, to CPV line, to Parker line, to I-225 line, and lastly to the WC line.

Car-borne installation and testing will take from two to four weeks per vehicle. Vehicle installation should commence as soon as possible and in parallel to wayside installation. Use three weeks per vehicle as an assumption, retrofitting the entire 201 LRV fleet will take 603 weeks or 16.75 years if no parallel work is implemented. The retrofit time will be shortened if Model SD-100’s LRV will be retired and not used in SSO corridors. Depends on the LRV conditions and construction schedule, an alternative implementation method shall be developed to match the cut-over time for each corridor.

Upgrading the OCC for SSO implementation should be performed in parallel with installing the first SSO corridor.

For the new SSO Signal System to realize the most significant benefit from replacing the infrastructure at the critical interlockings, it would make the most sense to include the renewals of the old VHLC signal processor ElectrologIXS part of the project, under the contractor’s control. This would keep issues of phasing and coordination on the Contractor minimizing the potential for delays caused by the interface of multiple projects in the same territory.

Estimated Implementation Schedule

For reference purposes, the contract time frames for SSO/CBTC systems implementation in some US projects are NYCT about 10 Years, MUNI approximately 8 Years, SEPTA about 8 Years, and BART about 11 years.

Time frames for SSO systems implementation in RTD LRT will depend on the technology chosen, contracting method, design and construction, construction phasing, and other factors. Table 6 below illustrates a sample estimated SSO implementation schedule.

The field equipment will be installed in parallel with the back office and vehicle installations. Typically, the installer requires a minimum of four hours of unimpeded time when installing and testing the wayside equipment. It is anticipated that the field equipment installation will be accelerated once the installation on the first corridor is completed and tested.

Year		1		2		3		4		5		6		7		8
Month	6	12	18	24	30	36	42	48	54	60	66	72	78	84	90	96
Planning and Contract Development	■	■														
Pre-bid/Bid and Award			■													
Contractor Design Submittal & Review				■	■	■	■	■	■	■	■	■	■	■		
Manufacture of Equip. & Factory Testing					■	■	■	■	■	■	■	■	■	■		
OCC Installations						■	■	■								
Vehicle Installations						■	■	■	■	■	■	■	■	■	■	
Field Installations & Testing, SW 8.7 mile						■	■	■								
Field Installations & Testing, SE 17.3 mile								■	■	■	■					
Field Installations & Testing, CC 5.3 mile										■	■					
Field Installations & Testing, CPV 1.8 mile											■					
Field Installations & Testing, PR 4 mile											■	■				
Field Installations & Testing, I225 10.5 mile												■	■	■		
Field Installations & Testing, WC 12 mile													■	■	■	
Certifications																■

Table 6 - Sample SSO/CBTC Implementation Schedule

The sample schedule illustrates how the eight-year time frame will be used from the commencement of planning/design to completion. Some strategies could be adopted to reduce the SSO Project Schedule.

Rough Cost Estimate

In general, the rough cost estimation of SSO implementation in freight railway is about

$300,000 per route mile. Due to denser and more complicated track infrastructure in urban areas, passenger and commuter railway costs are signifying higher than for freight railway, with cost in many cases exceeding $1 million per mile. A recent example was in October 2020, BART awarded a $798 million contract to design, build, and install the CBTC technology to replace the existing ATC system on 125 route miles of tracks, a separate $45 million consult engineering service contract is also awarded.

There is a wide range of variables that have an impact on the cost of SSO system implementation. Table 7 below provides a high-level rough cost estimation and is for early assessment purpose only.

ID	ITEM	Formula	Cab Signal SSO ($MM)	Balise SSO ($MM)	CBTC SSO ($MM)	CBTC Moving Block ($MM)
A	DB Contract		20	38	47	58
B	201 LRV Onboard Retrofit		28	66	50	60
C	Subtotal Construction	A+B	48	104	97	118
D	Consultant Engineering Service	C*10%	5	10	10	12
E	RTD PM & CM	C*20%	10	21	19	24
F	Contingency	(C+D+E)*30%	19	41	38	46
G	Subtotal Other Costs	D+E+F	33	72	67	81
H	Total Rough Project Cost	C+G	81	177	164	200
I	Escalation (3% / year | 4 years)	(1*3%)^4	10	22	21	25
J	Total Adjusted Rough Project Cost	H+I	91	198	185	224

Table 7 - RTD LRT SSO/CBTC Implementation Rough Cost Estimations

Appendix

List of LRT Signal system Relay Houses and Cases and type of Equipment

RTD LRT SIGNAL SYSTEM RELAY HOUSES/CASES

XL – INTERLOCKING
IS - INTERMIDEATE SIGNAL
CS - CUT SECTION
ELS - ELECTRIC LOCK & SWITCH
SI - SWITCH INDICATOR
CL- COLOR LIGHT SIGNAL
ES - EMBEDDED SWITCH
AHCW - AUTOMATIC HIGHWAY CROSS WARNING
RH - RELAY HOUSE
RC - RELAY CASE
SIG - SIGNAL

CORRIDOR	MILES	RH/RC	ABS RH	SIG
CC	5.4	25	18	27
CPV	1.8	13	13	21
WC	12.1	53	53	108
SW	8.7	21	21	30
SE	17.3	49	49	70
I225/PR	14.5	52	39	63
TOTAL	59.8	213	193	319

CC CENTRAL-CORRIDOR

NAME		SIZE	TYPE
RC16CC	0321+95	2'x7'	SI,ES, NON ABS
RC60ACC	0299+45	2'x4'	NON ABS
RC70CC	0293+80	2'x7'	SI,ES, NON ABS
RC126CC	0264+35	2'x7'	SI,ES, NON ABS
RC168CC	0241+60	2'x7'	SI,ES, NON ABS
RC201CC	0229+90	2'x7'	SI,ES, NON ABS
RC219CC	0214+50	2'x5'	TWC, NON ABS
RH237CC	0204+51	4'x6'	XL, CPVJ
RC250CC	0102+70	2'x5'	XL, CPVJ
RC270CC	0191+50	8'X12'	XL, 13TH ST
RH13XCC	0188+50	8'X8'	XING
RH281CC	0181+50	8'X8'	IS

RH300CC	0171+52	8'X8'	IS
RC321CC	0164+01	2'x5'	XL, N YARD
RH324CC	0161+89	8'X12'	XL, N YARD
RC352CC	0145+17	2'x5'	XL,YARD
RH358CC	0141+75	8'X12'	XL, S YARD
RH379CC	0126+60	8'X8'	IS
RH422CC	0099+55	8'X8'	IS
RH426CC	0092+00	8'X8'	IS
RH474CC	0075+90	8'X8'	IS
RH481CC	0073+81	8'X8'	IS
RH495CC	0295+93	8'X12'	XL, S ALAMEDA
RH526CC	0053+50	8'X12'	XL, BURK
RH540CC	0019+00	10'X20'	XL, N BRDWY

CC	5.4 MI
# OF RH/RC	25
# OF XL RH	8
# OF IS/CS RH	8
# OF X/CKT RH	2
# OF NON ABS	7
# OF SIGNAL	27

CPV - CENTRAL PLATT VALLEY CORRIDOR

NAME		SIZE	TYPE
RH253CP	0104+95	8'X12'	XL, CPVJ
RH255CP	0108+90	10'X20'	XL, CPVJ
RH256CP	0110+20	4'X6'	XL, CPVJ
RH286WC	0114+74	10'X20'	XL, CPVJ
RH265CP	0119+40	6'x8'	XL, WALNUT
RH266CP	0119+41	6'x6'	XL, WALNUT
RHWXCP	0124+30	8'X8'	IS,AHCW
RH337CP	0152+60	8'X8'	IS,ELS
RH357CP	0163+20	8'X12'	XL, PEPSI N.
RH382CP	0178+35	8'X12'	XL, DUT
RH384CP	0181+45	8'X12'	XL, DUT
RH394CP	0187+97	6'X8'	XL, DUT
RH396CP	0190+50	8'X12'	XL, DUT

CPV	1.8 MI
# OF RH	13
# OF XL RH	11
# OF IS/XING RH	2
# OF SIGNAL	21

SW - SOUTHWEST CORRIDOR

NAME		SIZE	TYPE
RH544SW	0322+04	10'X20'	XL S BRDWY
RC547SW	0328+00	2'x5'	XL S BRDWY
RH588SW	1018+00	6'X6'	IS

RH648SW	1001+00	6'X6'	IS
RH661SW	0982+00	6'X6'	IS
RH696SW	0964+09	6'X6'	IS
RH739SW	0953+08	8'X10'	XL ELA N
RH743SW	0945+35	8'X10'	XL ELA N
RH790SW	0901+25	8'X10'	XL ELA S
RH856SW	0882+79	6'X8'	CS
RC888SW	0862+00	2'x5'	ELS
RH900SW	0848+00	6'X8'	IS
RH968SW	0815+42	6'X8'	CS
RH1011SW	0772+00	6'X8'	IS
RH1121SW	0736+64	6'X8'	IS
RC1175SW	0708+00	2'x5'	ELS
RH1221SW	0683+65	6'X8'	IS
RH1223SW	0678+88	6'X8'	IS
RH1334SW	0524+70	6'X8'	IS
RH1392SW	0599+32	6'X6'	XL MINERL
RH1393SW	0591+86	8'X12'	XL TAIL

SW	8.7 MILE
# OF RH	21
# OF XL RH	7
# OF IS/CS RH	14
# OF SIGNAL	30

WC - WEST CORRIDOR

NAME		SIZE	TYPE
RH295WC	1636+10	8'X12'	XL,COLFAX
RH311WC	1625+55	6'X8'	IS
RHZUXWC	1615+54	8'X12'	IS,AHCW
RH340WC	1607+11	6'X8'	IS
RHDEXWC	1597+49	8'X12'	IS,AHCW
RH371WC	1593+49	8'X12'	XL, FED
RH382WC	1588+72	6'X8'	IS
RH395WC	1580+36	6'X8'	IS
RH411WC	1571+33	6'X8'	IS
RHKNXWC	1567+31	8'X12'	IS,AHCW
RH431WC	1562+26	6'X8'	IS
RH451WC	1555+00	6'X8'	IS
RHPEXWC	1546+36	8'X12'	IS,AHCW
RH471WC	1541+37	6'X8'	IS
RH490WC	1530+55	6'X8'	IS
RH530WC	1508+77	6'X8'	IS
RH541WC	1503+90	6'X8'	IS
RH569WC	1488+31	6'X8'	IS
RHHAXWC	1478+15	6'X8'	CS, AHCW

RH600WC	1470+41	6'X8'	IS
RHLAXWC	1464+96	8'X12'	IS,AHCW
RHPIXWC	1450+97	8'X12'	IS,AHCW
RHTEXWC	1439+37	6'X8'	CS,AHCW
RH680WC	1427+93	6'X8'	IS
RH691WC	1423+29	6'X8'	IS
RH716WC	1409+00	6'X8'	IS
RHCAXWC	1398+96	6'X8'	IS,AHCW
RH749WC	1392+38	8'X12'	XL, ESTE
RHESXWC	1386+50	6'X8'	CS,AHCW
RH781WC	1377+67	6'X8'	IS
RHGAXWC	1372+35	8'X12'	IS,AHCW
RHINXWC	1359+95	8'X12'	IS,AHCW
RH850WC	1338+95	6'X8'	IS
RHOAXWC	1320+27	8'X12'	IS,AHCW
RH901WC	1314+51	6'X8'	IS
RHQUXWC	1305+75	8'X12'	IS,AHCW
RHCOXWC	1292+58	8'X12'	IS,AHCW
RH8XWC	1270+28	8'X12'	IS,AHCW
RHNOXWC	1245+80	6'X8'	IS,AHCW
RH1048WC	1238+00	8'X12'	XL FDCE
RH1052WC	1233+22	6'X8'	IS
RH1064WC	1227+91	6'X8'	XL FDC
RH1082WC	1224+18	8'X12'	XL FDC
RH1090WC	1214+98	10'X12'	XL FDCW
RH1140WC	1188+00	6'X8'	CS
RH1194WC	1153+37	8'X12'	XL RR
RH1214WC	1148+23	8'X12'	XL RRW
RH1281WC	1101+38	6'X8'	CS
RH1343WC	1079+32	6'X8'	CS
RH1401WC	1052+24	6'X8'	CS
RHULXWC	1030+85	6'X8'	CS, AHCW
RHEJXWC	1018+22	6'X8'	IS, AHCW
RH1470WC	1012+74	8'X12'	XL JCGC

WC	12.1 MILE
# OF RH	53
# OF XL RH	10
# OF IS/CS RH	43
# OF SIGNAL	108

SE - SOUTH EAST CORRIDOR

NAME		SIZE	TYPE
RH583SE	0021+54	10'X20'	XL KTK
RH589SE	0033+84	8'X10'	XL KTK
RH618SE	0061+57	6'X6'	IS, ELS
RH625SE	0066+15	6'X6'	IS
RH661SE	0084+35	6'X8'	IS
RH710SE	0108+85	6'X6'	IS
RH714SE	0113+58	6'X6'	IS
RH783SE	0148+31	6'X8'	IS, ELS
RH823SE	0167+50	6'X8'	IS
RH864SE	0195+66	6'X8'	IS
RH915SE	0218+80	6'X8'	IS
RH939SE	0243+00	6'X8'	IS, ELS
RH971SE	0257+25	6'X8'	IS
RH1033SE	0289+00	6'X8'	IS
RH1087SE	0315+70	6'X6'	IS
RH1120SE	0334+36	6'X6'	IS
RH1127SE	0338+86	8'X12'	XL SM
RH1141SE	0350+05	8'X12'	XL SM
RH1169SE	0358+50	6'X6'	IS
RH1203SE	0376+80	10'X20'	XL SMJ
RH1250SE	0398+00	6'X8'	XL SMJ
RH1277SE	0417+99	10'X20'	XL SMJ
RH1283SE	0422+30	6'X6'	IS
RH1332SE	0447+53	6'X8'	IS, ELS
RH1384SE	0519+70	6'X6'	IS
RH1391SE	0524+01	6'X6'	IS
RH1439SE	0552+00	6'X8'	IS
RH1482SE	0573+15	6'X6'	IS, ELS
RH1486SE	0578+30	6'X6'	IS
RH1533SE	0598+43	6'X8'	IS
RH1559SE	0608+49	6'X6'	IS
RH1589SE	0630+27	6'X6'	IS
RH1644SE	0657+68	6'X6'	IS
RH1651SE	0662+60	6'X6'	IS, ELS
RC1697SE	0687+20	2'X7'	IS, ELS
RH1730SE	0697+59	6'X8'	IS
RH1770SE	0724+96	6'X8'	IS
RH1831SE	0754+30	6'X8'	IS
RH1881SE	0776+50	6'X6'	XL LKN
RH1886SE	0780+85	6'X6'	XL LKN
RH1887SE	0786+00	10'X14'	XL LKPN
RH1920SE	0802+95	10'X14'	XL LKPS

RH1947SE	0818+25	6'X6'	IS
RH1976SE	0833+00	6'X8'	IS
RH1985SE	0838+43	8'X14'	IS
RH2036SE	0862+60	8'X10'	IS
RH2045SE	0869+70	8'X10'	IS
RH2088SE	0891+40	10'X14'	XL RGN
RH2103SE	0896+00	10'X20'	XL RGS

SE	17.3 MILE
# OF RH	49
# OF XL RH	14
# OF IS/CS RH	35
# OF SIGNAL	64

PR - I225/PARKER CORRIDOR

NAME		SIZE	TYPE
RH1255PR	0049+64	6'X8'	XL SMJ
RH1245PR	0056+55	6'X8'	XL SMJ
RH1216PR	1207+55	6'X8'	XL SMJ
RH1260PR	1233+80	10'X20'	XL SMJ
RH1351PR	0517+50	6'X8'	IS, ELS
RH1400PR	0539+07	6'X6'	IS
RH1407PR	0542+85	6'X6'	IS
RH1458PR	0575+00	6'X8'	IS
RH1508PR	0601+06	6'X8'	IS
RH1569PR	0633+00	8'X10'	XL NINE M
RH1592PR	0646+66	6'X8'	IS
RH1622PR	0661+33	8'X12'	XL NINE M
RH1675PR	0691+91	6'X8'	IS
RH1744PR	0726+90	6'X8'	IS
RH1759PR	0735+07	6'X8'	IS
RH1815PR	0764+70	6'X8'	IS
RH1864PR	0789+75	6'X6'	IS
RH1875PR	0795+45	8'X12'	XL FL
RH1885PR	0802+20	8'X12'	XL FL
RH1911PR	0815+10	6'X6'	IS
RH1933PR	0827+00	6'X6'	IS
RH1959PR	0840+58	6'X8'	IS END ABS
RC2053PR	0889+95	2'X5'	CL, NON ABS
RHALXPR	0897+75	6'X8'	AHCW, NON ABS
RHCOXPR	0902+26	6'X8'	AHCW, NON ABS
RHBAXPR	0907+93	6'X8'	AHCW, NON ABS
RH2119PR	0924+74	8'X12'	XL EW BEGIN ABS

RHELXPR	0930+98	6'X8'	AHCW
RH2152PR	0942+09	8'X8'	IS
RH2AXPR	0942+31	6'X8'	AHCW
RH2167PR	0950+24	6'X6'	IS
RH4AXPR	0957+40	6'X8'	AHCW
RH2214PR	0974+85	6'X8'	IS
RH2263PR	1000+99	8'X12'	XL 13S
RH2291PR	1015+51	8'X12'	XL 13N
RH2322PR	1032+20	6'X8'	IS
RH2333PR	1037+74	6'X6'	IS
RH17AXPR	1046+23	6'X8'	AHCW
RH17PXPR	1051+16	6'X8'	AHCW
RH2388PR	1066+80	6'X8'	IS,AHCW
RH2418PR	1082+47	6'X6'	IS
RHURXPR	1104+42	6'X8'	AHCW
RH2466PR	1108+43	8'X12'	XL FS
RH2481PR	1115+90	6'X6'	IS
RHSCXPR	1121+03	6'X8'	AHCW
RH2527PR	1140+88	6'X8'	IS
RH30XPR	1164+40	6'X8'	AHCW
RH31XPR	1172+08	6'X8'	AHCW
RH33XPR	1181+53	6'X8'	AHCW
RH2604PR	1181+81	6'X8'	IS
RH2634PR	1196+27	8'X12'	XL POR
RH2644PR	1201+93	8'X12'	XL TAIL

PR-I225	14.5 MILE
# OF RH	52
# OF XL RH	13
# OF IS/CS RH	26
# OF AHCW	13
# OF SIGNAL	63