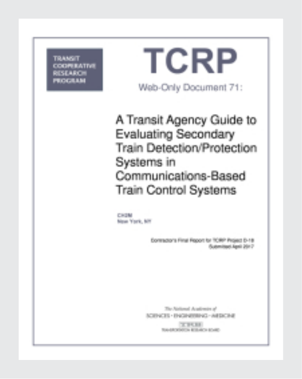


A Transit Agency Guide to Evaluating Secondary Train Detection/Protection Systems in Communications-Based Train Control Systems

DETAILS

93 pages | 8.5 x 11 | PAPERBACK
ISBN 978-0-309-47407-8 | DOI 10.17226/25063

CONTRIBUTORS

CH2M; Transit Cooperative Research Program; Transportation Research Board; National Academies of Sciences, Engineering, and Medicine

TCRP

Web-Only Document 71:

A Transit Agency Guide to Evaluating Secondary Train Detection/Protection Systems in Communications-Based Train Control Systems

CH2M
New York, NY

Contractor's Final Report for TCRP Project D-18
Submitted April 2017

ACKNOWLEDGMENT

This work was sponsored by the Federal Transit Administration (FTA) in cooperation with the Transit Development Corporation (TDC). It was conducted through the Transit Cooperative Research Program (TCRP), which is administered by the Transportation Research Board (TRB) of the National Academies of Sciences, Engineering, and Medicine.

COPYRIGHT INFORMATION

Authors herein are responsible for the authenticity of their materials and for obtaining written permissions from publishers or persons who own the copyright to any previously published or copyrighted material used herein.

Cooperative Research Programs (CRP) grants permission to reproduce material in this publication for classroom and not-for-profit purposes. Permission is given with the understanding that none of the material will be used to imply TRB, AASHTO, FAA, FHWA, FMCSA, FRA, FTA, Office of the Assistant Secretary for Research and Technology, PHMSA, or TDC endorsement of a particular product, method, or practice. It is expected that those reproducing the material in this document for educational and not-for-profit uses will give appropriate acknowledgment of the source of any reprinted or reproduced material. For other uses of the material, request permission from CRP.

DISCLAIMER

The opinions and conclusions expressed or implied in this report are those of the researchers who performed the research. They are not necessarily those of the Transportation Research Board; the National Academies of Sciences, Engineering, and Medicine; or the program sponsors.

The information contained in this document was taken directly from the submission of the author(s). This material has not been edited by TRB.

The National Academies of
SCIENCES · ENGINEERING · MEDICINE

TRB
TRANSPORTATION RESEARCH BOARD

The National Academies of
SCIENCES • ENGINEERING • MEDICINE

The **National Academy of Sciences** was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. C. D. Mote, Jr., is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.national-academies.org**.

The **Transportation Research Board** is one of seven major programs of the National Academies of Sciences, Engineering, and Medicine. The mission of the Transportation Research Board is to increase the benefits that transportation contributes to society by providing leadership in transportation innovation and progress through research and information exchange, conducted within a setting that is objective, interdisciplinary, and multimodal. The Board's varied committees, task forces, and panels annually engage about 7,000 engineers, scientists, and other transportation researchers and practitioners from the public and private sectors and academia, all of whom contribute their expertise in the public interest. The program is supported by state transportation departments, federal agencies including the component administrations of the U.S. Department of Transportation, and other organizations and individuals interested in the development of transportation.

Learn more about the Transportation Research Board at **www.TRB.org**.

Copyright National Academy of Sciences. All rights reserved.

Contents

Tables

Figures

Foreword

TCRP Web-Only Document 71: A Transit Agency Guide to Evaluating Secondary Train Detection/ Protection Systems (STD/PS) in Communications-Based Train Control (CBTC) Systems discusses STD/PS technologies and types of CBTC, and provides guidelines for evaluating the implementation of STD/PS on a CBTC rail network.

The deployment of a new signaling system requires a closely coordinated partnership among rail transit agencies, CBTC and STD/PS suppliers, installers, oversight agencies, and other stakeholders. This guide will be helpful to rail transit agencies, signaling system suppliers, consultants, safety regulators, grant writers, policy boards, and other stakeholders in evaluating the need for, and selection of, an appropriate STD/PS technology for CBTC deployment projects.

This guide has been developed as a result of the research effort conducted by the CH2M team through review of industry literature and a study of previously completed and ongoing CBTC projects to identify scope and factors relative to the selection of deployment strategies and technology choices. The research effort was based on the collection of data pertaining to deployment experience, operational practices, and technical aspects of a CBTC system with and without STD/PS. The principal means for collecting this data were visits and interviews with rail transit agencies and CBTC suppliers involved in major CBTC projects.

The research approach involved a two-phase process. The first phase focused on data collection and compilation utilizing literature review and industry surveys of rail transit operators and CBTC suppliers to understand the decision-making processes behind STD/PS implementation. The second phase of the research focused on the selection of rail transit agencies for case studies, which involved direct site visits, in-person interviews, observation and data collection on typical CBTC operating practices and reliance on STD/PS. This guide has been developed with the help of six CBTC implementation case studies.

Author Acknowledgments

The Transit Agency Guide to Evaluating Secondary Train Detection/Protection Systems (STD/PS) in Communications-Based Train Control (CBTC) Systems was conducted through the Transit Cooperative Research Program (TCRP), which is administered by the Transportation Research Board (TRB) of the National Academy of Sciences. This guide was developed under TCRP Project D-18 by the CH2M New York City-based rail transit team (prime contractor), and supported by Integrated Strategic Resources (ISR) Consultants.

The CH2M team was led by Kenneth Diemunsch, CSEP (Principal Investigator). The co-investigators were Stuart Landau, PE, MIRSE, Signal and Train Control Engineer; Girish Ananthashankaran, Senior System Engineer; Tedd L. Snyder, PE, Senior System Engineer; Stuart Hymowitz, Signal Engineer; Muamer Dedović, Rolling Stock System Integration Engineer; and Robert F. Spero, Rail Operations Specialist. Special thanks go to Elizabeth Royzman and Christine Martino for their project support in compiling the information received from different agencies and overall assembly of the guide, and Girish Ananthashankaran for providing guidance during the project.

The project team thanks the transit agencies and CBTC suppliers who took the time to meet with the project team, accommodate requests for information, arrange for tours of their facilities, participate in the survey and case studies, and provide feedback on CBTC systems and projects around the world. Their assistance and input were invaluable in helping to shape this guide. In particular, the team thanks the agencies which participated in the case studies: New York City Transit (New York, NY, USA); Transport for London (London, UK); AirTrain JFK (New York, NY, USA); Maryland Transit Administration – Baltimore Metro Subway (Baltimore, MD, USA); British Columbia Rapid Transit Company (Vancouver, BC, Canada); and Port Authority Trans-Hudson (Jersey City, NJ, USA).

The project team thanks the following signaling suppliers for their valuable contributions: Ansaldo Signaling and Transportation Systems (Pittsburgh, PA, USA); Alstom Transport (Saint-Ouen, France); Bombardier Transportation (Pittsburgh, PA, USA); China Railway Signal & Communication Co. (Shanghai, China); Siemens Mobility – Rail Automation (Châtillon, France); Thales Transportation Solutions (Toronto, ON, Canada); and Frauscher Sensortechnik GmbH (Marienkirchen, Austria).

The project team thanks the TCRP D-18 Board for their support and overall feedback on the project.

Abstract

The top priorities of any signaling system have always been ensuring safe movement and separation of trains, prevention of injury to personnel and patrons, and optimization of system capacity. These objectives can be achieved by using various service-proven and mature technologies. The advantages of Communications-Based Train Control (CBTC) technology are substantial. In addition to capacity increase, the system offers the potential to optimize maintenance effort, operational flexibility, and system management capabilities, thereby maximizing the overall return on capital investment. Despite the fact that operating and performance benefits of CBTC technology have been well demonstrated on many systems around the world over the past decades, some agencies still prefer to supplement it with a secondary train detection/Protection System (STD/PS). This STD/PS may consist of a conventional interlocking implementation with track circuits or axle counters.

The purpose of this guide is to provide a practical approach to evaluating the appropriate level of STD/PS for a given CBTC application. In terms of detection, track circuits and axle counters are both considered and compared, including the broken rail detection capabilities of track circuits and the possibility of having no secondary detection at all.

The first part of this guide presents different STD/PS technologies, and discusses CBTC deployment trends and feedback on operations from rail transit agencies around the world. The second part provides guidance for selection of an appropriate level of STD/PS, in terms of candidate technologies, product maturity, and potential risks. This evaluation is intended to be used during the early stages of CBTC procurement projects. Case studies are provided at the end of the guide.

Summary

Communications-Based Train Control (CBTC) is one of the most advanced train control systems available to transit agencies; it enables transit agencies to make maximum use of the infrastructure configuration by allowing the trains to run closer to each other in comparison to other signaling systems. Deployment of CBTC technology in the United States has been limited so far due in part to a perception of higher cost and apparent difficulty with implementation and operation of this technology in comparison with other signaling systems. This perception of high cost is primarily driven by the expectation that CBTC systems require an additional, independent signaling system to detect and protect trains in the event of CBTC system failure. This is particularly true for re-signaling projects in a *brownfield* environment (that is, an upgrade of an existing system; compared to *greenfield* projects which are new clean-sheet systems) where the implementation of CBTC must consider existing operational, maintenance, and infrastructure constraints. Research was conducted to evaluate the need for an additional signaling system and the different types of signaling systems that could be used to manage CBTC failures. The research resulted in the present guide; its goals are to help transit agencies decide if an additional signaling system is needed, and if so, the appropriate type of secondary system.

The Institute of Electrical and Electronics Engineers (IEEE), Std 1474.1, Standard for Communications-Based Train Control, Performance and Functional Requirements, defines CBTC as a continuous automatic train control (ATC) system utilizing:

- High-resolution train location determination, independent of track circuits
- Continuous, high capacity, bidirectional train-to-wayside data communications
- Train-borne and wayside processors capable of implementing vital functions

The four primary components of a CBTC system are:

- Train-borne equipment
- Wayside equipment
- Data communications equipment
- Automatic Train Supervision (ATS) equipment

CBTC has been used for more than 30 years all around the world in mass transit projects, initially on new lines and progressively on signaling upgrade projects where the transit agencies needed to address one or more requirements including:

- Improved capacity
- Replacement of a system at end of life
- Enhanced train protection with continuous speed enforcement
- Enhanced roadway worker safety

CBTC has been used for all modes of train operation, from manual to driverless. It has been deployed on a wide range of transit modes, from airport people movers, to light rail systems, to metros/subways, and to commuter rail lines.

In addition to CBTC, an additional signaling system is usually considered and implemented that provides back-up in the case of CBTC failures (both wayside and carborne) and to support unequipped trains, such as work trains. The additional signaling systems in this guide will be referred to as secondary train detection/protection systems (STD/PS) or simply secondary systems, which provide train detection as well as train protection functions. Another name commonly used is “fallback system,” given that it is used in the event of CBTC system failures. They are called secondary systems or auxiliary wayside systems because CBTC is the primary train control system. All worldwide CBTC suppliers have experience

experience with secondary signaling systems and can offer integrated solutions as part of their respective CBTC packages.

Either *track circuits* or *axle counters* can be used for train detection. Several types of track circuits have been used by the rail industry for more than a century, using the rails as part of a circuit to detect the presence of trains. Train wheels and axles shorting the rails together de-energize a track relay or other detection device to indicate occupancy. If a wire or rail breaks, the effect is the same as a train occupying the track circuit; this is an operational nuisance but more importantly, is safe since approaching trains will be stopped. The operation is simple, continuous, and fail-safe.

Axle counters are a proven technology and have been used for decades, although they have very limited implementations in the United States. This technology uses wheel sensors attached to the running rails that detect passing train wheels (axles). Evaluator equipment then computes the difference between the number of wheels entering an area and the number exiting the area to determine train presence. Some of the reasons why the use of axle counters has been limited in the United Sates is because the transit agencies are familiar with track circuits, have developed trust in their performance for achieving train detection, and because, unlike track circuits, axle counters are not able to detect broken rail. However, despite these reasons, more and more CBTC projects are using axle counters as a secondary method of detection.

The industry survey resulted in the following CBTC project categories:

Table 1: CBTC Project Categories

Category	Type
1.A	**Secondary System capable of revenue service**
1.A.1	Secondary System capable of peak revenue service
1.A.2	Secondary System capable of off-peak revenue service
1.B	**Secondary System designed to handle a single non-CBTC train**
1.B.1	Capable of one train per interstation
1.B.2	Capable of one train in between two interlockings
1.B.2.1	With detection devices everywhere
1.B.2.2	With detection devices only at interlocking
1.B.3	Without territory specific headway performance
2	**No Secondary System**

Two key consequences of having an STD/PS are the effort to deploy the new signaling system and the additional maintenance needed to maintain both the secondary system and the CBTC system. These key consequences impact the cost of deployment and the operation of the system. Another major consequence of having a secondary system is that the availability of the overall signaling system is lower than with CBTC only. This can be due to having more equipment to support both systems and a corresponding increase in overall system complexity. It is important to keep these drawbacks in mind when considering the benefits of having an additional signaling system.

Alternatively, not having an STD/PS has two drawbacks: reliance on procedures in case of CBTC failures, which is vulnerable to human error, and the potential need to equip some of the work trains with CBTC technology to allow for mixed operation with both CBTC and non-CBTC trains without impact to revenue service.

The result of the industry survey showed that work trains are handled differently by each transit agency without any direct relationship to the presence or type of secondary system. The method to manage work trains does not necessarily need to influence the selection of a secondary signaling system. There are different prevalent methods of managing work train operation:

- Use operating procedures to manage work train movement. This could be a challenge to manage for transit agencies that operate 24/7.
- Equip work trains with CBTC equipment, capable of full CBTC protection or capable of reporting position only, with the protection being managed by operating procedure. Equipping work trains can be implemented by fitting onboard equipment on the train or by attaching a trailer or locomotive equipped with CBTC.

The different factors to consider when selecting the possible secondary system appropriate for a specific transit agency are summarized below:

Table 2: Selection Factors of an STD/PS

#	STD/PS Purpose	Comments
1	Mixed-fleet operation	The need for mixed-fleet operation with CBTC and non-CBTC trains is mainly related to the cut-over strategy with regards to the integration of the onboard CBTC equipment on the trains. Where not all trains are equipped with CBTC at the beginning of CBTC operations, a secondary system capable of peak performance is needed (Category 1.A.1), at least temporarily, until all CBTC trains are equipped and the system can be changed to another category.
2	Run peak headway	Based on the industry survey, the only possible reason to deploy and maintain an STD/PS capable of peak headway performance is if trains which are not equipped with CBTC are operating often on the line. This may be the case on part of the lines where trains from non-CBTC lines need to transfer from the yard to their own operating line. The need to run a peak headway results in Category 1.A.1. A system capable of peak operation may also be useful during the cut-over period from the legacy system to the new CBTC system. In some cases, projects have started being compatible with peak headway (Category 1.A.1) and then modified to only provide off-peak revenue service in a second step (Category 1.A.2).
3	Back-up for revenue service	Though the availability of a CBTC system is usually specified as more than 99%, the issue of having a fallback system is often raised for CBTC projects deployed on a particularly busy line. Characteristics of the lines such as alternative modes of transportation, crowd control, or distance between stations should be considered. This option corresponds to a 1.A.2.
4	Management of a single train with CBTC failure	This matter is closely related to the need for a back-up system for the complete line and similar considerations should be taken into account. Results may show that there is no need to have a full back-up system able to handle wayside CBTC failure, but there is a need to manage a single train with CBTC failure efficiently and automatically by a signaling system instead of completely by operating procedures. In this case, project Category 1.B is selected. Depending on the ratio between operating procedures and automatic management of a single train with CBTC failure, projects have decided to opt for Category 1.B.1, 1.B.2, or 1.B.3.

#	STD/PS Purpose	Comments
5	Management of Work Trains	Managing work trains is not necessarily part of the decision process. When managing work trains, the selection process must consider if the transit agency has 24/7 operation, where work trains would operate around and with CBTC revenue service trains. In this case, either the decision is made to equip work trains with CBTC or there must be a secondary system to facilitate their operation, and projects in Category 1.B would be sufficient. For projects with a secondary system, similar to the management of a single train with CBTC failure, depending on the headway performance required for work trains, agencies could opt for Category 1.B.1, 1.B.2, or 1.B.3.
6	Broken Rail Protection	Broken rail protection is an important issue considered in CBTC projects and may result in the perception of needing track circuits. Results of the research show that broken rail protection should not influence the decision to have a secondary system. There are two prevalent methods to provide broken rail protection: detect broken rails using track circuit failure indications or detect rail flaws by inspection and correct the issue before the break happens. Inspection is done both visually and with ultrasonic equipment.

When comparing track circuits and axle counters, it appears that for CBTC secondary detection, axle counters have a slight advantage. Axle counters may be installed in parallel to existing track circuits, thus facilitating the cut-over on a signaling upgrade program. Also, axle counters have no constraint on the length of the block which they monitor, in comparison to track circuits which have a maximum length. This factor suits a CBTC secondary system where block lengths in a secondary system are likely to be longer than in a conventional signaling system.

Regulatory and technical aspects must also be considered with the engineering team prior to selection of an STD/PS. From a regulation point of view, this research only identified Federal Railroad Administration (FRA) rules that mandate track circuits, and only one rapid transit agency falls in this category. A transit agency should check with their regulatory authorities to confirm whether track circuits are mandated. From a technical point of view, the conditions of the tracks and rail inspection program must be discussed with the team in charge of maintenance of the tracks. Evidence suggests that agencies could be using more rigorous rail inspection methods to thwart the catastrophic rail break, regardless of the STD/PS solution. Even with track circuits, only certain rail flaws, such as clean breaks, are detectable without inspection.

The guide includes various case studies conducted during the research. All categories of CBTC projects are considered with feedback on the experience in deployment and operations. All transit agencies studied had different approaches and the CBTC projects considered range widely in time periods and maturity level of the technology, from when CBTC originally emerged, to projects which have not been awarded. Therefore, the solution for each project is very different and covers a range of perspectives and lessons learned. The goal of the case studies is to make the research comprehensive and provide example templates for transit agencies trying to make selection decisions in similar situations.

SECTION 1

Introduction

A continuous need to address passenger growth, enforce safe operation, and more effectively utilize rail transit infrastructure has led many urban mass transit operators to adopt new technologies. The evolution and adoption of Communications-Based Train Control (CBTC) technology over the past decades have grown significantly, which in turn made it a widely accepted signaling system for both new mass transit projects and replacements/upgrades of legacy signaling systems.

CBTC’s capabilities provide an advanced means to safely control rail traffic while increasing throughput and shortening headways. However, the selection of CBTC technology and application strategies can pose some significant challenges, especially when modernizing existing transit lines with goals to achieve specific benefits and return on capital investment.

This publication seeks to assist transit agencies considering a CBTC system with understanding the need for supplementing CBTC with a secondary train detection/Protection System (STD/PS) or the use of operating procedures in lieu of an STD/PS. It must be made clear that CBTC does not require a secondary or fallback system, and the decision whether to use one should be based primarily on the agency’s requirements for managing non-CBTC trains which may be either non-CBTC equipped trains or trains with CBTC failure.

The guide identifies general characteristics of CBTC systems and types of STD/PS used to supplement them, and then discusses common operating procedures/practices by transit agencies which operate CBTC with or without the STD/PS. This guide discusses different factors to consider when deciding on the STD/PS, with emphasis on both benefits and drawbacks of available methods. Sorted by relevance, those factors should be used together with the decision flow diagrams to aid the selection process.

Acknowledging the fact that every transit agency is different, the goal of this guide is not to derive straightforward solutions for a particular case or situation or to set forth any rules, nor does it attempt to substitute the exercise of systematic thorough studies when assessing and selecting CBTC technology.

This guide was developed using information gathered from leading CBTC signaling suppliers and transit agencies operating under CBTC. The guide aims to provide direction on the method of reasoning for decision makers. It illustrates the importance of major factors leading to a solution, helps to support a transit agency’s choice, and provides a means to formalize the thought process.

SECTION 2

Problem Statement

According to IEEE 1474.1-2004 – IEEE Standard for CBTC Performance and Functional Requirements,

> “A CBTC system is a continuous, automatic train control system utilizing high-resolution train location determination, independent of track circuits; continuous, high capacity, bidirectional train-to-wayside data communications; and train-borne and wayside processors capable of implementing automatic train protection (ATP) functions, as well as optional automatic train operation (ATO) functions and automatic train supervision (ATS) functions.”

CBTC allows trains to operate safely at shorter headways and permits system operations to recover more rapidly in the event of service delays. These features offer a more regular and improved passenger service which can translate into increased line capacity, constrained only by the performance of the rolling stock and the limitations of the physical track alignment. One of the fundamental operational benefits of CBTC systems is that movement authority limits are no longer constrained by physical fixed-block boundaries, but are established through train position reports that can provide “virtual block” or “moving block” control philosophies.

Per Federal Transit Administration (FTA) Report No. 45, An Assessment of the Business Case for CBTC:

> “To date, deployment of CBTC technology within the United States has been limited, due, at least in part, to a perception of higher costs associated with the implementation of this technology. This perception of higher costs is in turn driven, in part, by a perception that CBTC systems require a secondary track circuit-based or axle counter based ‘fallback’ system to detect and protect trains in the event of CBTC system failures.”

This guide examines why some transit agencies have elected to implement STD/PS in their CBTC projects, while others have successfully deployed CBTC without it, opting to rely strictly on operating practices and rules. The result is that different types of CBTC systems with different levels of STD/PS (from non-existent to a full system) are used throughout the world. The reasoning for selecting a particular CBTC architecture and feedback on experience are described in this guide, in order to help transit agencies considering CBTC make the decision on what level of STD/PS, if any, is preferred for their system.

SECTION 3

List of Acronyms

APTA	American Public Transportation Association
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATP	Automatic Train Protection
ATS	Automatic Train Supervision
BCRTC	British Columbia Rapid Transit Co.
CBTC	Communications-Based Train Control
CC	Carborne Controller
CENELEC	Comité Européen de Normalisation Électrotechnique (European Committee for Electrotechnical Standardization)
CFR	Code of Federal Regulations
DC	Direct Current
FRA	Federal Railroad Administration
FTA	Federal Transit Administration
IEEE	Institute of Electrical and Electronics Engineers
JFK Airport	John F. Kennedy International Airport
MTA	Metropolitan Transportation Authority or Maryland Transit Administration
NYCT	New York City Transit
LUL	London Underground Limited
OBCU	OnBoard Control Unit
PATH	Port Authority Trans-Hudson
PTC	Positive Train Control
STD/PS	Secondary Train Detection/Protection System
TCRP	Transit Cooperative Research Program
TRB	Transportation Research Board
UPS	Uninterruptable Power Supply
VCC	Vehicle Control Center
VOBC	Vehicle Onboard Controller

SECTION 4

CBTC Technology

4.1 CBTC Equipment

As defined in FTA Report No. 45, CBTC is a train control system

> "using two-way communications between intelligent trains and wayside computers. An intelligent train is defined as a train that can determine its own location and that calculates and enforces safe operating speeds without the use of track circuits or wayside signals. In CBTC systems, the exact position of a train is known more accurately than with track circuit-based signaling systems. CBTC systems also offer opportunities for improved safety and operational performance, in addition to reduced life cycle cost."

From the definition of CBTC comes the four primary components:

- Train-borne equipment
- Wayside equipment
- Data communications equipment
- Automatic Train Supervision (ATS) equipment

4.1.1 CBTC Train-Borne Equipment

CBTC train-borne equipment consists of one or more processor-based controllers, associated odometry and data communications devices, and location determination sensors. It interfaces with major train subsystems, wayside, and the ATS equipment via the data communications equipment. It is responsible for train location determination, the enforcement of permitted speed and movement authority limits, and other allocated train-borne automatic train protection (ATP) and Automatic Train Operation (ATO) functions.

4.1.2 CBTC Wayside Equipment

CBTC wayside equipment consists of a network of processor-based wayside controllers installed at central and/or wayside locations. Each wayside controller interfaces with the CBTC train-borne equipment and ATS equipment via the data communications equipment. CBTC wayside equipment also interfaces with external interlockings, unless interlocking functions are included within the CBTC wayside equipment. The wayside intelligence for CBTC related ATP functions—such as movement authority settings based on the tracking of both CBTC equipped and unequipped trains, as well as other allocated wayside ATP, ATO, and ATS functions—resides in the CBTC wayside equipment. Train location determination is a train-borne function for CBTC equipped trains and a wayside function for unequipped trains. CBTC wayside equipment also includes any track-based equipment necessary to provide a unique absolute positioning reference to the CBTC train-borne equipment.

4.1.3 CBTC Data Communications Equipment

CBTC data communications equipment includes equipment located at the control center, wayside locations, and onboard the train to support the wayside-to-wayside, wayside-to-train, train-to-wayside, and train-borne data communications. Onboard equipment can also support trainline data communications for applications featuring multiple carborne controllers. Such data links are capable of bidirectional data transfer and feature sufficient bandwidth with low latency needed to efficiently support all defined ATS, ATP, and ATO functions. The communications protocols support timely and secure delivery of vital train control messages.

4.1.4 CBTC ATS Equipment

CBTC ATS equipment includes equipment installed at the control center and/or wayside locations. This equipment handles ATS (non-vital) functions such as identifying, tracking, and displaying trains, providing manual and automatic route setting capabilities, regulating train movements to maintain operating schedules, and initiating temporary speed restrictions and work zones. ATS also interfaces with other systems such as passenger information systems which indicate when the next train is arriving at a station.

4.2 CBTC Train Control Modes

Modern CBTC can operate on several different levels of automation and control modes, typically tailored to specific preferences of a given operating agency. The level of control ranges from full automatic to manual operation with protection. This section discusses commonly adopted control modes of CBTC equipped trains.

4.2.1 CBTC Control Modes

The following are the most common CBTC control modes:

Full automatic operation

Whether fully driverless operation or with an attendant present onboard, the CBTC onboard system controls all operations, including train movement and door operation. No manual intervention by attendant is necessary for normal operations.

Partial automatic operation

An onboard attendant manually initiates train movement by depressing a start button. Upon validation of required departure conditions, the onboard controller controls the train movement until the next stop. The next stop might be in between stations, behind other trains, or at the next station platform.

Manual driving under CBTC protection

An onboard driver manually controls the train movement while the CBTC system provides ATP, including speed enforcement. The driver uses the master controller of the train to control the propulsion and brake systems.

4.2.2 Non-CBTC Control Modes

The following non-CBTC control modes apply to an individual train and not necessarily to several trains. The behavior of the following train is not dependent on the control mode of a train. When the train in non-CBTC control mode is localized by the CBTC system, the following train can close up to it, as if the non-CBTC control mode train were in CBTC mode.

Manual driving at slow speeds without CBTC protection (Restricted Speed mode)

When dealing with CBTC system failures or other specific operational conditions, driver(s) may be authorized to move affected train(s) without CBTC protection but under enforced fixed speed. The speed restriction might be enforced by the CBTC system, if available, or by the rolling stock equipment. Speed is limited to less than 25 mph. On systems where STD/PS cannot support revenue service, this mode would be the only authorized control mode in the event of a CBTC failure. In such cases, train movement is handled by operating procedures where there is no desire to reach revenue service speeds.

Manual driving without CBTC protection (bypass mode)

When operating in bypass mode, the attendant has full control of the train, with no speed enforcements by CBTC. Operation is in accordance with the STD/PS, if there is one available. Otherwise, this mode is for recovery and emergency train movement.

4.2.3 Other CBTC Control Modes

Yard operation

Where yards are under CBTC control but not fully automated, train movements can be performed by manual driving under CBTC protection or manual driving at slow speed without CBTC protection.

Manual driving without CBTC protection – out of CBTC territory

Upon detection that the train has left the CBTC territory, an onboard controller may be able to switch over to manual mode without the manual intervention by the driver. The train control consists of manual driving without CBTC protection.

Manual driving under civil speed enforcement

To mitigate the effect of CBTC system failures or because of a particular CBTC design in some areas of the line, the non-communicating onboard controller may operate in a type of degraded mode, still capable of enforcing civil speed limits.

4.3 Trends in CBTC Projects Around the World

The CBTC technology has evolved over the past four decades, mainly due to an increasing demand for alternatives to address aging signaling infrastructure and to achieve better operational performance. In addition to greenfield applications, many existing mass transit operations were forced to re-signal legacy infrastructure. Thus, over the past decade, brownfield projects surpassed the amount of greenfield applications.

CBTC brownfield projects currently represent the majority of the CBTC applications (except in Asia)

CBTC technology emerged in the 1980s and was mostly used for greenfield projects until the early 2000s, when brownfield projects become more prevalent. Brownfield projects are highly complicated and can last for almost a decade before completion. Often, the CBTC architecture for brownfield projects can be influenced by the choice of migration method to CBTC, resulting in the 1.A Category. In contrast, the use of STD/PS on greenfield type projects is occasional. When used, the STD/PS capabilities are limited to the 1.B Category.

Axle counter popularity is increasing

As a standalone detection system, axle counters have been in use since the 1960s, mainly in Europe and parts of Asia, Africa and Australia, but rarely on North American transit systems. Most CBTC systems don’t include an STD/PS, and those that do almost exclusively incorporate a track circuit based STD/PS. It was only recently that axle counter based STD/PS found its way into CBTC projects.

One of the reasons for this original overwhelming preference for track circuit based STD/PS is related to early diffusion of CBTC technology and target markets. Two out of the three original CBTC suppliers were based in France, a rail market which has a strong preference for track circuits and very few networks equipped with axle counters. The third original CBTC supplier, based in Canada, has had a completely different approach to that of its European counterparts—a CBTC system without STD/PS—and later was the first CBTC supplier to introduce an axle counter based STD/PS.

The axle counters are commonly used on brownfield CBTC type projects to facilitate migration from legacy systems to CBTC, as those can be fitted and operated independently of existing track circuits. This eases the conversion process and thereby minimizes the risk of service disruptions.

The industry opts for reduced levels of STD/PS functions

Deploying a CBTC system, especially in a brownfield project without interrupting passenger revenue service, is very challenging. Despite the experience acquired by suppliers over the past decades, there have been examples all over the world of projects being delayed or scaled down. The overall complexity of the system is one of the main reasons for the difficulties to deploy it. Eliminating or minimizing the level of STD/PS is a method to limit re-signaling project complexity.

In addition, there have been projects where CBTC operates very reliably and thereby reduces the real use of STD/PS, though transit agencies still ought to maintain it and bear an upkeep cost.

For these reasons, users opt to select an STD/PS with reduced capabilities, able to manage a single non-CBTC train but unable to support peak or off-peak revenue service.

Driverless systems are becoming more popular

There is a recent trend around the world for driverless systems, either greenfield or brownfield. Driverless systems are less favorable to having STD/PS mainly because of the need to send personnel onboard the train to recover from a failure. Though not all new driverless projects are without STD/PS, one can expect that the proportion of projects without STD/PS will grow along with the progression of driverless projects.

CBTC suppliers have limited CBTC experience without STD/PS

All industry leading CBTC suppliers have project experience featuring an STD/PS, both with track circuits and axle counters. However, not all suppliers have experience with mass transit projects without STD/PS. There have been only a dozen of such projects without STD/PS in the world.

The survey revealed that, to date, all brownfield CBTC projects feature some form of a STD/PS. In other words, only greenfield projects have been implemented without STD/PS so far.

SECTION 5

Secondary Train Detection/Protection Systems

In the context of CBTC, a secondary train detection/protection system (STD/PS) is a signaling system comprised of, but not limited to:

- A secondary train detection system only, or
- Both secondary train detection and secondary train protection systems.

As defined in IEEE 1474.1-2004 – IEEE Standard for CBTC Performance and Functional Requirements, an STD/PS, also referred to as an auxiliary wayside system, is:

> “A back-up or secondary train control system, capable of providing full or partial ATP for trains not equipped with train-borne CBTC equipment and/or trains with partially or totally inoperative train-borne CTBC equipment. The auxiliary wayside system may include train-borne equipment and may also provide broken rail detection.”

STD/PS can support both vital functions (e.g. train separation) and non-vital functions (e.g. route selection). It is what is usually thought of as “conventional” signaling.

The term “secondary” is a misnomer, as STD/PS usually provides “primary” safety functions that are relied upon by CBTC. In addition to the vital safety functions, CBTC may rely on STD/PS for non-vital functions, such as route selection.

Wayside systems have a long history with varied implementation. A typical implementation includes track circuits, wayside signals, wayside logic, and enforcement devices. A rapid transit application might include alternating current track circuits, color-light signals, relay-based logic, and wayside trippers to enforce red signals. Variations from this basic application includes:

- Mechanical interlocking machines
- Processor-based wayside logic
- Coded track circuits for cab signaling with onboard speed enforcement, in which case wayside signals and trippers might only be located at interlockings or not at all
- Audio frequency track circuits, in which case insulated joints might be eliminated
- Axle counters

Careful consideration goes into the layout and spacing of STD/PS blocks and signals to achieve safe train separation and a desired headway based on train performance and authorized speeds. Signals may be spaced far apart with long blocks where speeds are higher and headways longer; or they may be spaced closer with shorter blocks where speeds are lower and headways shorter. For signaling modernization projects using CBTC, the existing STD/PS may be kept as is or modified to provide some semblance of normal service. A modified STD/PS with CBTC may provide longer headway than under full CBTC. This is usually acceptable since operating under STD/PS-only operation is a back-up during CBTC failures or for unequipped work trains, and is not expected to provide maximum throughput under these circumstances.

For brownfield projects, the industry survey showed that there have been existing wayside systems that have remained as is, some that have been modified, and some that have been completely replaced with the installation of CBTC.

Among the legacy systems replaced by CBTC technology, one finds two systems: conventional signaling systems which do not use any onboard electronics; and cab signaling which is another type of advanced train control system using onboard electronics and train-wayside communications such as coded track circuits. So far, there have been very few projects in the world where a CBTC system was replaced by another, but it is expected to be more frequent as the first CBTC systems reach their end of life. Due to problems such as space on board the trains, obsolescence, and availability of onboard electronic equipment, the secondary systems considered in CBTC projects are conventional signaling systems and not cab signaling or other type of ATC.

5.1 Detection Systems

5.1.1 Track Circuits

Regardless of the technology used to implement safety principles of STD/PS, the foundation of STD/PS is train detection, and traditionally this has been the track circuit. The Association of American Railroads defines a track circuits as:

> “An electrical circuit of which the rails of the track form a part.”

A track circuit is a section of track with a source of energy connected across the running rails at one end of the track section (the “feed” end) and a device that is operated by this energy at the other end of the track section. The device has traditionally been an electromechanical relay, so this end of the track circuit is called the “relay” end. Under normal conditions, there is no train or other vehicle occupying the track section. The energy at the feed end energizes the detection device at the relay end using the rails as conductors; the circuit is closed and the energized detection device indicates vacancy of the track circuit. When a train enters the section, its metal wheels and axles provide a low-resistance path from rail to rail for the feed energy, greatly reducing or eliminating energy at the relay end that would be available for the detection device. The device then becomes de-energized and indicates occupancy of the section. The track circuit status is used by the signal system to provide safe separation between trains and other safety functions.

Note that under failure conditions, such as a broken wire, disconnected wire, missing feed, blown fuse, broken rail, etc., the circuit opens. The detection device de-energizes and indicates occupancy even though there may not be a train present. This is a safe failure since it will be assumed by the signal system that there is a train occupying the section, keeping other trains a safe distance away.

A track is divided into a continuous sequence of track circuits arranged end-to-end. Each circuit may also be referred to as a track section, or section. One or more track sections comprise a block whose entrance is governed by a signal. Track circuits are physically and electrically isolated from each other with insulated joints in one or both rails at each end. If insulated joints are in both rails, impedance bonds are needed at track circuit boundaries to allow traction (vehicle motor) return current to flow unimpeded around the insulated joints.

Early track circuits were powered by batteries and thus used direct current. On electrified railroads, the running rails of the track are used as the traction current return path to the substation. If the traction current is direct current, the track circuit will be alternating current to minimize interference. Instead of a battery feeding the track circuit, a transformer is used to step-down the utility supply voltage.

Types of track circuits:

- Direct current (dc): early track circuits and in remote locations where utility alternating current is not available.
- Alternating current (ac): where dc traction is used.

- Coded: The steady energy used in the non-coded track circuit is modulated at certain rates. The modulation rates represent wayside-to-train information sent from the feed end toward receiving equipment on a train for transmission of information such as speed codes in conjunction with non-CBTC automatic train control and onboard speed enforcement.
- Audio frequency (AF): can eliminate insulated joints.

Track circuits are periodically tested by placing a shunt of a certain value across the rails at each end of the track circuit to ensure that the detection device indicates occupancy. A typical value of the shunt, and the value required to be used by Title 49 of the Code of Federal Regulations (CFR) § 236.56, is 0.06 ohms.

Operation and adjustment of track circuits are affected by the environment, most notably the track structure itself. There are electrical leakage paths between the rails through the ties and ballast and distributed throughout the track circuit. This is usually referred to simply as “ballast resistance.” To energize the detection device under vacant conditions, a track circuit adjusted with low ballast resistance (high leakage) will need to be driven hard to account for current lost through the ballast. If conditions change and the ballast resistance increases, the same circuit will be over-driven and the detection device may not respond to an occupied condition; this is an unsafe failure since an occupied block may indicate as vacant. A possible remedy is to adjust the track circuit under dry (low leakage) conditions. If leakage increases, the track itself may become enough of a load to falsely indicate the presence of a train, but this is a safe-side failure.

Track circuits can only reliably detect certain types of broken rail. If the break is sufficient to separate the ends of the rail or to introduce sufficient resistance in the rail, the track circuit will open and indicate occupancy to the signal system. This will set approaching signals to red to protect an approaching train from an incident. This is an important feature of track circuits, especially when compared to axle counter detection systems. Reports suggest that most kinds of rail defects still allow sufficient current to flow and will not be detected by the track circuit.

Title 49 C.F.R. § 236.51 requires track circuits to detect broken or missing rail, in addition to occupancy by trains. This regulation also recognizes that some breaks will not be detected, such as between the end of rail and the track circuit connector or where bypassed by a rail joint bond.

Unlike axle counters which require a special initialization process, track circuits report the correct occupancy status immediately and continuously after being powered up, assuming they are adjusted properly and all components and connections are intact.

5.1.2 Axle Counters

Whereas track circuits provide “continuous” detection of trains while any axle is within the section, the operation of axle counters is “intermittent.” That is, physical detection of trains takes place by detecting and counting the passage of wheels at the entering and leaving end of the track section or block.

Assuming the normal state, the axle counting equipment presumes a given section to be vacant. As a train enters the section, train wheels are detected and counted, and the section now indicates as occupied. When the same number of wheels are detected leaving the section as have entered the section, the section indicates as vacant. If, for example, a car is left behind, the number of wheels leaving will be less than the number of wheels entering, and the section will still be considered occupied.

Wheel detectors can be installed in pairs to detect travel direction of a train. This supports a train reversing movement in the axle counter block and allows exiting the way it entered. Average speed can be derived by measuring the detection time between two sensors at a known distance apart.

Compared to track circuits, there are few restrictions on the placement of axle counters. Track circuits use the rails as part of the circuit; axle counters do not. The rails are only used for mechanical mounting of the wheel detectors. Therefore, there is no concern for ballast leakage or rail resistance; little concern for traction current interference; no need for modifying the rail (or compromising its structural integrity) for insulated joints or to connect track wires and impedance bond cables.

Since axle counters do not know the absolute state of their track section when they are powered up, there must be an initialization process which involves intervention of humans who know the state of the section. This must be done only when the section is truly clear and may require field confirmation. This may also require the first train after reset to enter and leave the track section—while sweeping the section visually—before accepting the axle counter state as valid.

Manual intervention might also be needed in the case of a disturbed section, as might happen if the number of leaving wheels is more than the number of entering wheels since there cannot be a "negative" number of wheels left behind in the section.

5.2 Protection Functions

Train detection lays the foundation for train protection. A train being detected is vitally mandatory for protection from a following train. An occupied block prevents the clearing of signals approaching the occupied block. In interlockings, detection additionally effects certain types of locking to provide route integrity, locking of movable rail in the route and under the train, and preventing release of said locking before it is safe to do so. The following summarizes some of these functions.

5.2.1 Automatic Block Signal System

Between interlockings, STD/PS provides protection where each signal's control is arranged such that it will display red if a block in advance is occupied. The spacing between the red signal and the beginning of the occupied block is sufficient to provide safe braking distance if a train ignores the red and passes it at maximum speed. The signal will display yellow if the block in advance is vacant, but the next signal in advance is red. It will display green if the next signal is permissive (green or yellow); that is, there is a minimum number of blocks in advance that are vacant such that the train need not reduce speed nor prepare to reduce speed.

Automatic block signals may also include timers for Grade Time and Station Time controls. Grade Time controls enforce a maximum average speed in areas of descending grades and curves and is a means of overspeed protection using conventional signaling technology. Station Time controls support closing-in moves and allow signals in approach to occupied stations to clear sooner than would otherwise be permitted, if the approaching train's average speed is low enough. In CBTC systems, where STD/PS is used, the Grade Time and Station Time controls are usually not used.

5.2.2 Interlocking

Where there are controlled signals and movable switches, interlocking circuits ensure that all switches are aligned properly and locked for the desired route before signals may be allowed to clear; no conflicting routes may be established; no conflicting signals may be cleared; and a cleared signal locks all switches in the selected route.

- **Approach locking**. In effect when a signal is requested to clear. Activates route locking. Delays the release of route locking when the signal is cancelled with a train in approach. This prevents the hazard of a signal being cancelled in advance of a moving train with the intention of changing the route and the approaching train not being able to stop before reaching the interlocking.
- **Route locking**. Locks all switches in the requested route. Keeps them locked while a train movement is in progress over the route.

- **Detector locking**. Locks a switch while the track section that includes the switch is occupied. Prevents movement of the switch where such movement could cause a derailment. Release of detector locking is usually delayed to prevent premature unlocking due to momentary loss of shunt across the track circuit.
- **Traffic locking**. Where a single track between two interlockings is used for movements in both directions, traffic locking prevents conflicting (head-on) movements into the track against the established direction. To change the traffic direction, every track section within the traffic territory must be vacant.

When used with CBTC, STD/PS functions simultaneously and provides these safety functions for all trains, even equipped and communicating trains. CBTC is an overlay on STD/PS and provides the enhanced operations with closer headway and automatic train operation with speed and movement enforcement. Hence, parts of STD/PS are not quite "secondary;" they are required to provide basic interlocking protection for all trains, both CBTC and non-CBTC. In automatic block territory, for CBTC trains, the STD/PS following-move protection is overridden by the CBTC overlay to provide closer headways and onboard enforcement of train separation.

5.2.3 Methods of Enforcement of STD/PS

Mass transit conventional signaling systems often include a method to stop the train, in case a manually driven train overruns a signal at stop. The method may be a mechanical device on the roadbed, called a train stop or tripper. An arm on the roadbed device is raised when its associated signal is at stop. The raised arm engages a tripcock on a train which causes the release of brake air pressure on the train, causing an irrevocable emergency stop. The same function may be implemented using a radio frequency transponder or a magnetic device in the roadbed and a receiver device on the train.

Both types of enforcement require equipment onboard, underneath the train. Equipping every train with such a device is a burden that only transit agencies already using the device in the legacy system are willing to accept. The same method of enforcement may be used to enforce average speed by incorporating a timer that represents an approach time at maximum authorized speed. If the train's average speed is higher, the train reaches the stopping device before the timer disables it and a stop is enforced.

For cab signaling systems the communication of the authorized speed is through the rails and is continuous; the enforcement is an onboard function, so no other wayside device is necessary. Trains using cab signaling may or may not have an additional system able to enforce signals at stop, when the cab signal is not used. There have been examples of both cases in North America.

5.3 STD/PS Implementations

5.3.1 Categories of Secondary Systems

Based on the industry survey conducted as part of this research, CBTC projects can be grouped into two major categories: systems that feature STD/PS (Category 1) and systems that do not (Category 2).

Among the systems with STD/PS, there are two major subcategories from a functional point of view, those capable of handling some level of revenue service (Category 1.A) and those designed only to handle a single non-CBTC train (Category 1.B). Non-CBTC trains can be trains with CBTC failure or trains not equipped with CBTC, such as work trains.

Within Category 1.A, there are two subcategories. One identifies STD/PS systems able to manage peak revenue service (Category 1.A.1) in case of complete CBTC system unavailability or to manage non-CBTC equipped trains with revenue service headway performance. The second sub-category includes systems capable of an off-peak level of revenue service (Category 1.A.2), where a reduction in service is possible during a complete CBTC failure or to manage non-CBTC equipped trains.

Category 1.B includes STD/PS designed to handle a single non-CBTC train. There are also different subcategories based on performance desired when handling a single non-CBTC train. The first sub-category allows one single train per interstation (Category 1.B.1). Another sub-category includes managing a single non-CBTC train in between two interlockings (Category 1.B.2). In this sub-category, there are projects with secondary detection devices on the entire line that allow tracking of non-equipped trains (Category 1.B.2.1), or train tracking only in the interlocking area (Category 1.B.2.2). Finally, there is Category 1.B.3 without territory specific headway performance where a non-CBTC train is tracked by the CBTC system to allow operation of other CBTC trains around it.

In summary:

Table 3: STD/PS Functional Categories

Type	Category	Sub-category
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**
	1.A.1	Secondary System capable of peak revenue service
	1.A.2	Secondary System capable of off-peak revenue service
	1.B	**Secondary System designed to handle a single non-CBTC train**
	1.B.1	Capable of one train per interstation
	1.B.2	Capable of one train between two interlockings
	1.B.3	Without territory specific headway performance
Systems without STD/PS	**2**	**No Secondary System**

Finally, each sub-category is divided into projects using track circuits and projects using axle counters. For projects with axle counters, it is common that in addition to the axle counters at an interlocking or around a station, there are some axle counters used by the CBTC system for technical reasons or for mitigating a safety hazard. The axle counters are usually located at a wayside controller boundary to facilitate handover between controllers and at the transition between non-CBTC territory and CBTC territory to detect a non-CBTC train entering the CBTC territory.

From the industry survey, it can be noted that there was no project with a secondary system capable of revenue service (Category 1.A), peak or off-peak, which was using axle counters. There was no greenfield project in the Category 1.A with a secondary system capable of revenue service, peak or off-peak. Only greenfield projects have CBTC without STD/PS. Greenfield projects do not have the challenge of transitioning to CBTC and since they provide a new service they are less concerned with having a back-up system to run revenue service, relying instead on the high availability of the CBTC system elements.

5.3.2 Graphical Representation

To visualize the type of secondary system layout for each category of project, simplified typical layouts are presented in this section. Signals are present to show accuracy of control of the trains running under STD/PS. For the sake of simplicity, enforcement devices are not represented in the following figures.

Category 1.A.1 – Secondary system capable of peak revenue service

- Signals present at interlockings, around stations, and in between stations

- For trains operating under STD/PS, signals are usually automatically enforced
- Secondary detection system present everywhere

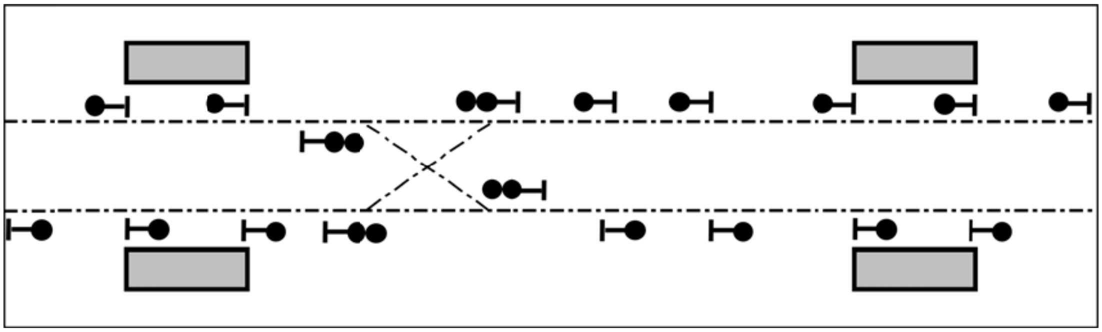


Figure 1: Category 1.A.1

Category 1.A.2 – Secondary system capable of off-peak revenue service

- Signals present at interlockings, around stations, and in between stations
- For trains operating under STD/PS, signals are usually automatically enforced
- Less equipment in between stations than in Category 1.A.1
- Secondary detection system present everywhere

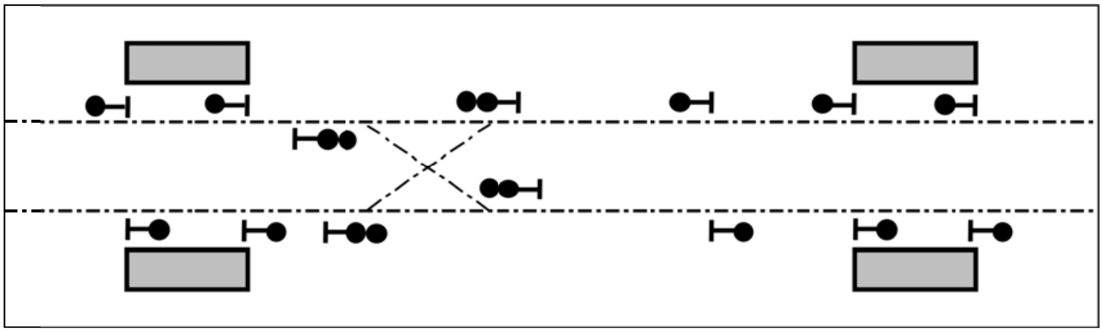


Figure 2: Category 1.A.2

Category 1.B.1 – Secondary system designed to handle a single non-CBTC train, capable of one train per interstation

- Signals at interlockings and at stations
- For trains operating under STD/PS, signals may be automatically enforced
- Secondary detection system present everywhere

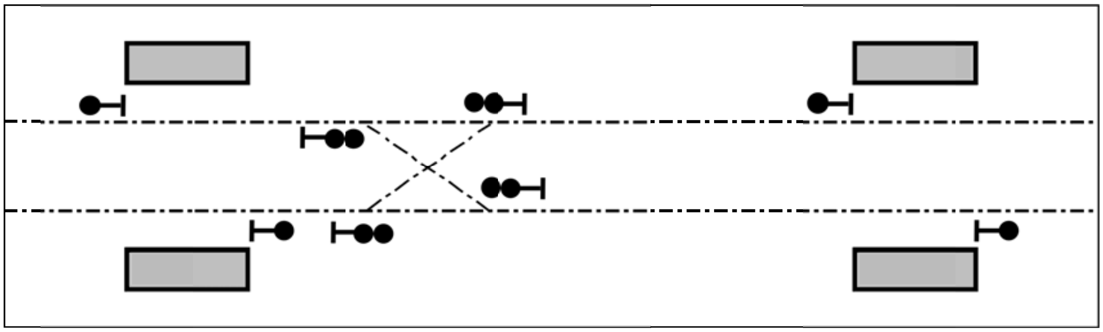


Figure 3: Category 1.B.1

Depending on the track layout (distance between stations and locations of the interlockings), having signals only at stations and around interlockings may be sufficient to run off-peak headway (Category 1.A.2).

Category 1.B.2.1 – Secondary system designed to handle a single non-CBTC train, capable of one train between interlockings, with secondary detection method everywhere

- Signals at interlockings
- For trains operating under STD/PS, signals are usually not enforced automatically
- Secondary detection system present everywhere

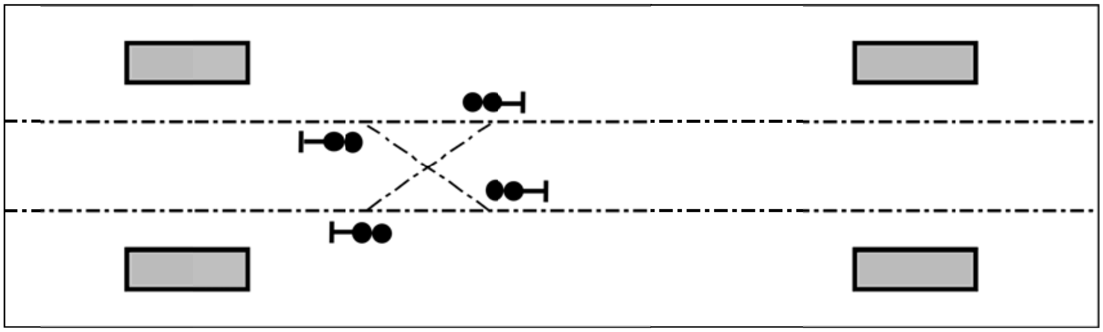


Figure 4: Category 1.B.2.1

Category 1.B.2.2 – Secondary System designed to handle a single non-CBTC train, capable of one train between interlockings, with secondary detection method only at interlockings

- Signals at interlockings
- For trains operating under STD/PS, signals are usually not enforced automatically
- Secondary detection system present only at interlockings

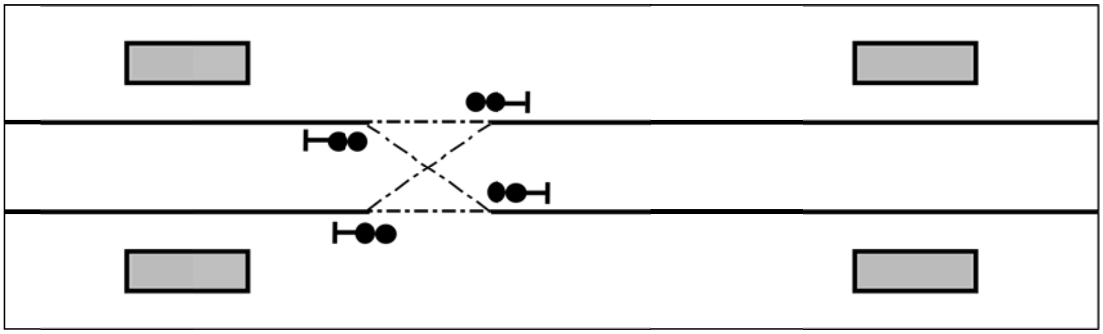


Figure 5: Category 1.B.2.2

Category 1.B.3 – Secondary System designed to handle a single non-CBTC train, without territory specific headway performance

- No signals
- Secondary detection system present everywhere

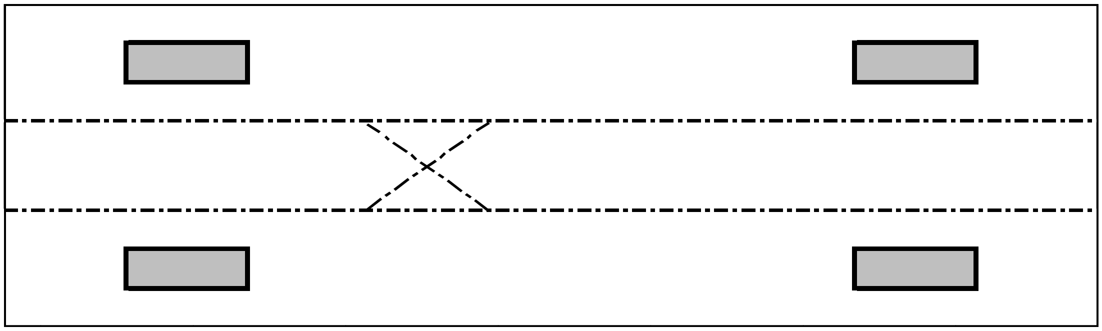


Figure 6: Category 1.B.3

Category 2 – No STD/PS

- Systems without STD/PS
- No secondary detection system

Switch position indicators showing the position of switches to manual drivers are usually used when no interlocking signals are present; however, they are not represented in the following figure.

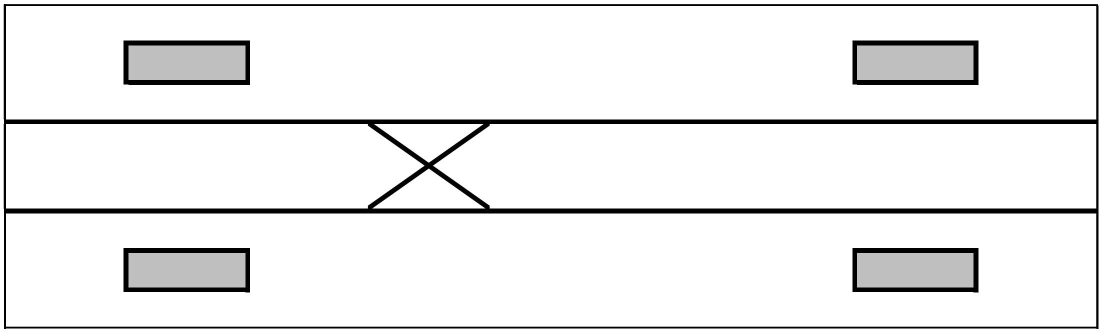


Figure 7: Category 2

SECTION 6

STD/PS Considerations

6.1 Consequences of Having an STD/PS

Below are the consequences of a secondary system in a CBTC project:

6.1.1 Investment Effort

A secondary system requires a significant investment effort to deploy. In comparison to deploying CBTC without STD/PS, a CBTC project with STD/PS requires a higher capital cost and a longer schedule due to:

- More effort to design the STD/PS and the added complexity of integrating the STD/PS with CBTC.
- More equipment to purchase and install. Installation is usually the major cost and could be a major impact on the schedule for signaling upgrade projects.
- More tests in the field, with more issues to fix, in particular at the interface between STD/PS and CBTC.
- More agency oversight with both CBTC and STD/PS skills with a wider range of expertise.

6.1.2 Maintenance Effort

The inclusion of STD/PS adds to the overall life cycle cost. Additionally, maintenance required for the STD/PS throughout the operating life of the new CBTC project is an added expense.

Note that one of the arguments in favor of deploying CBTC technology is that CBTC requires less equipment on the track and therefore less maintenance actions by roadway workers. This is also seen as a method to improve safety for agency personnel. Having an STD/PS which needs maintenance actions on the track lower this CBTC benefit.

6.1.3 Impact on CBTC Operation Availability

Transit agencies have increased focus on reliability and system availability during acquisitions and project development. The goal is to achieve high-reliability performance to minimize the impact of equipment failures on revenue service. An increase in devices may include components on or near the track, which are subject to adverse weather conditions or damage by other maintenance activities. Increasing equipment count and complexity inherently implies more probable failures and adverse effects on the availability of the signaling system. The impact on availability can be assessed analytically using reliability and availability methods. The negative impact on the CBTC operation availability appears to be one of the most important considerations by transit agencies for limiting the level of STD/PS.

6.1.4 Example of Technical Challenges for Integrating STD/PS in CBTC Project

This section presents some of the reasons why integration of an STD/PS in a CBTC project is complex. One of the primary reasons for implementing CBTC technology is to improve system capacity by enabling more trains to operate on the same infrastructure. Technically, conventional signaling systems could be designed to meet performance close to CBTC performance, but it would require a large amount of wayside equipment to have similar capabilities.

Conventional signaling systems are based on fixed blocks and assume that the train is running at its maximum authorized speed when calculating the safe distance between two trains. Block layout and signal spacing are based on the worst-case conditions and therefore the system is generally not optimal for operation under normal conditions. On the other hand, CBTC, using the exact location and instantaneous speed of the trains, continuously calculates the varying safe separation which results in minimum possible distance between two trains at all times.

The conventional signaling system may be capable of enforcing signals at stop, via devices mounted on the roadbed. The train stop arm activating a tripcock which opens the emergency brake lines on the train is one such example. To have the CBTC system provide its optimal train separation, allowing trains to be closer to each other than the conventional system, the conventional train separation enforcement system must not affect CBTC trains. The transit agency may also want to avoid the issue of having CBTC trains passing non-proceed signals, even if those signals are dedicated for the non-CBTC trains.

In rare cases, transit agencies have decided that CBTC trains should respect the conventional signaling system with non-optimal train separation.

There are several methods to avoid the conventional signaling system impeding on CBTC performance:

- Disable the enforcement system and have a separation signal which is clearly only for the non-CBTC trains, such as a particular color.
- Have the CBTC system override the enforcement system and override the signals so that signals present an aspect different for the CBTC trains than for the non-CBTC trains. For example, a solid green indicates STD/PS proceed and a flashing green indicates CBTC proceed. This approach increases not only the complexity of the CBTC itself but also the complexity of the secondary system.

6.1.5 Evaluating the Adverse Consequences of STD/PS

One undisputed benefit of having an STD/PS is that it allows operators better management of trains during CBTC failures. More sophisticated STD/PS will in turn have the most impact on the baseline CBTC system, such as:

- High capital investment with deployment of the new/replacement signaling system
- Higher maintenance efforts and life cycle cost
- Impact on overall system availability. Having an STD/PS allows continuing train operation without CBTC or in restricted CBTC modes and therefore it could be said to increase the complete signaling system availability. However, having an STD/PS whose failures affect CBTC operation decreases the probability of continuing to run in CBTC mode.

As part of the assessment process, agencies should also consider not having an STD/PS, described in the next section, and rely on:

- Operating procedures in case of CBTC failure
- Equipping work trains with CBTC

Depending on the CBTC system, operating procedures may also be needed to manage some STD/PS failures. However, failures of STD/PS are local to a specific geographical area around the failed equipment, whereas management of failures of the CBTC system implies using operating procedures to safely move one or more trains over a large portion of the territory.

Table 4 provides an example of an evaluation of the impacts of an STD/PS. The impacts are similar whether an STD/PS is track circuit or axle counter based. For each type, the STD/PS category is evaluated using zero percent (0%) where there is no STD/PS and one hundred percent (100%) where a complete conventional signaling system capable of peak service operates. Note that due to the need for integration between STD/PS and CBTC, the effort of a complete conventional signaling system as a secondary system to CBTC is higher than only having a complete conventional signaling system alone.

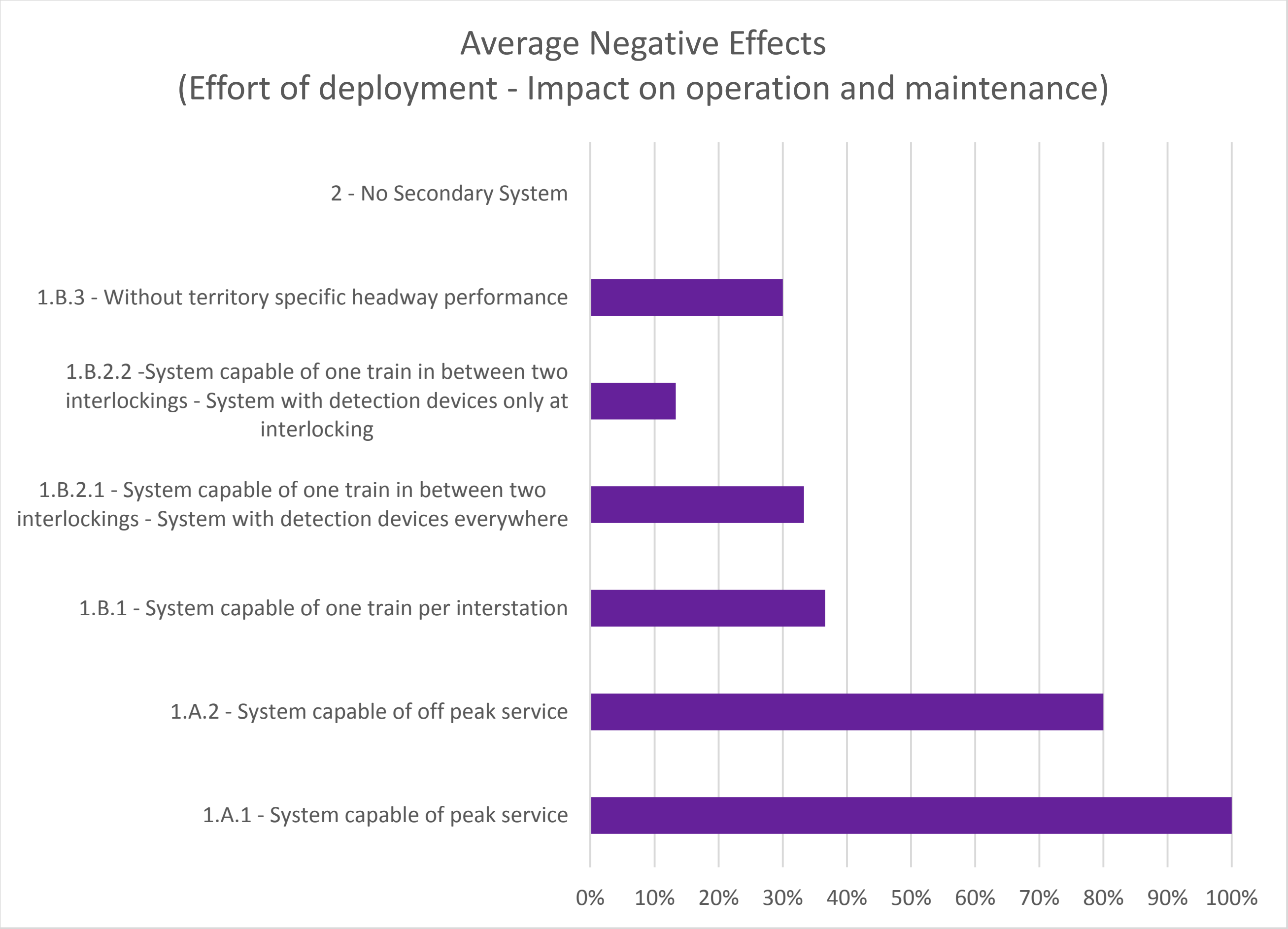
Transit agencies considering a CBTC project may apply a similar evaluation approach based on its experience. Points noted in Table 4 are illustrative and might vary for each transit agency.

Table 4: Examples of STD/PS Drawbacks (percentages are illustrative and will vary depending on system characteristics)

Type	Category	Sub-category	Investment effort (%)	Maintenance effort (%)	Impact on CBTC operation availability (%)	Avg (%)
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**				
	1.A.1	Secondary System capable of peak revenue service	**100**	**100**	**100**	**100**
	1.A.2	Secondary System capable of off-peak revenue service	**80**	**80**	**80**	**80**
	1.B	**Secondary System designed to handle a single non-CBTC train**				
	1.B.1	Capable of one train per interstation	**40**	**30**	**40**	**36**
	1.B.2	Capable of one train in between two interlockings				
	1.B.2.1	With secondary detection method everywhere	**40**	**30**	**30**	**33**
	1.B.2.2	With secondary detection method only at interlocking	**20**	**10**	**10**	**13**
	1.B.3	Without territory specific headway performance	**30**	**30**	**30**	**30**
Systems without STD/PS	**2**		**0**	**0**	**0**	**0**

The following chart helps visualize the consequence of implementing an STD/PS for each CBTC category:

Table 5: Level of Consequences of STD/PS – Average effort of deployment and impact on maintenance and operation (percentages are illustrative and will vary depending on system characteristics)



This graph shows the comparative level of effort required for each type of secondary system.

1. The difference between 1.B.2.2 with detection equipment only at interlocking and the group of 1.B.1, 1.B.2.1, and 1.B.3 with detection equipment everywhere is relatively important due to the difference in the amount of the equipment used for detection. The benefit of having detection equipment everywhere is that non-equipped trains can be tracked with accuracy while in 1.B.2.2, non-equipped trains can only be tracked with blocks as large as the distance between interlockings.
2. The difference in the level of efforts between 1.B.2.1/1.B.3 and 1.B.1 is low. This explains why there are few projects in the 1.B.2.1/1.B.3 Categories. For the similar amount of effort, the secondary system can manage a non-equipped train per interstation with minimal operating procedure.
3. The gap between 1.B.1 and 1.A.2 is significant and explains why it is important to only implement a system capable of peak or off-peak revenue service when absolutely needed.

In summary, the proposed generic example may explain why most new CBTC projects around the world, greenfield and brownfield, are selecting Category 1.B.1. For transit agencies unwilling to operate without a secondary system, this option allows managing a single train with CBTC failure and work trains with a relatively low investment on the secondary system.

Though the drawbacks of STD/PS are important during the selection process, they are not always directly influencing the choice of a CBTC system. One of the reasons may be the difficulty in quantifying the negative impacts.

6.2 Consequences of Having No or Minimal STD/PS

Not having an STD/PS could have the following impacts during initial deployment phases and during revenue service.

6.2.1 Relying Heavily on Operating Procedures

Handling of non-CBTC equipped trains, and trains with CBTC failure have been very challenging for systems without STD/PS in terms of the impact on system availability and operations. For equipment failures, as an example, location tracking of trains with CBTC failure is not possible, which makes automatic protection unlikely. In such cases, one must manually ensure:

- Protection of the non-equipped train or train with CBTC failure from the other CBTC trains.
- Protection of CBTC trains from the non-equipped train or train with CBTC failure.

These protections are accomplished at the control center by the ATS system operator. The protections rely on the ATS operator and train driver managing operating procedures.

Note that even in projects with STD/PS, handling trains with CBTC failure always requires relying partially on the secondary system and partially on operating procedures. The level of operating procedure is very minimal in project Categories 1.A and increases in projects in 1.B.1, 1.B.2, and 1.B.3.

Finally, operating procedures to handle trains not detected by the STD/PS should always be in place. Non-shunting vehicles, which may include hi-rail vehicles, for example, are managed entirely by operating procedures, whether an STD/PS is present or not.

6.2.2 Equipping Work Trains

Another consequence of not having STD/PS at all (Category 2) or having projects with low STD/PS level (Category 1.B.2) is that the need for equipping work trains may be more important. Section 8 – Work Trains presents the different methods of equipping work trains.

SECTION 7

Equipment Failures

7.1 CBTC Equipment Failures

7.1.1 Equipment Redundancy

To maintain a high level of service, train control suppliers have been working to include redundancies in their new systems. The most common methods used in CBTC projects are described below. The architecture discussed in this section concerns all CBTC equipment: onboard controller, wayside controller, and ATS servers. Both availability and safety affect the architecture of CBTC equipment. Safety features may require using several units and a comparison system, while higher availability is achieved by adding more redundant units.

1oo2: One out of Two

The most common type of redundancy is to have two identical units when only one is required for proper operation. This arrangement is called 1 out of 2 and denoted as 1oo2.

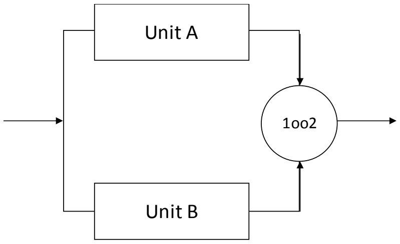


Figure 8: Example of 1 out of 2 redundancy architecture

The two units are configured in hot standby. With hot standby, one unit is active and the other is passive waiting to become active. If the active unit fails, then the passive unit becomes active.

2oo2: Two out of Two

For safety considerations, suppliers have developed a method which includes two identical hardware units performing the same functions (sometimes in two different ways) and a subsystem comparing the results of the two units. If the results match, then the result is validated and processed in terms of outputs. If the results of the two units do not match, the system is not able to conclude which result is correct, therefore it stops performing its function. This method is denoted as 2oo2 and is used to guarantee the integrity of the result for vital applications. This arrangement is usually combined within a 1oo2 system, with each redundant unit being made of two 2oo2 units (four units in total).

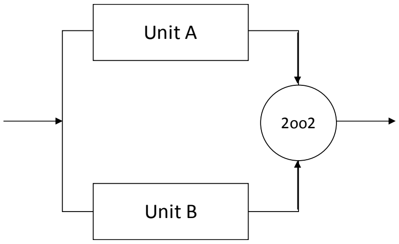


Figure 9: Example of 2 out of 2 redundancy architecture

This arrangement may be applied to vital systems such as onboard and wayside controllers. In practice, it is only applied to wayside equipment and not to onboard where the 1oo2 or 2oo3 is preferred. One of the constraints of this 2oo2 arrangement is that complete redundant 2oo2 equipment includes four units while other arrangements require two or three units. More units imply more space and more frequent maintenance which might be more acceptable for wayside controllers than for onboard controllers.

2oo3: Two out of Three

For vital systems, CBTC suppliers may expand the 2oo2 system by adding a third unit. It is called two out of three and denoted as 2oo3, where two out of three units must work properly and have identical outputs for the system to continue to function. Comparator logic compares the results of the calculations of the three units; at least two must agree for the system to function properly. If one unit has a different result than the other two, the troubled unit is isolated, i.e. its results are not considered until the failure is cleared.

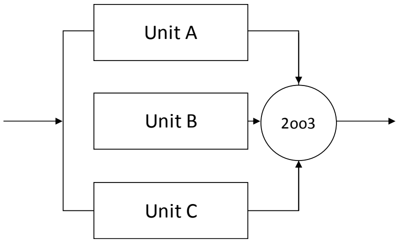


Figure 10: Example of 2 out of 3 redundancy architecture

This configuration may be applied to both the onboard and wayside controller depending on the CBTC project. Usually, the maintenance procedure requires that the complete equipment be down during repair even though only two units are necessary for operation. This constraint is not present on a redundant 2oo2 system which makes the 2oo2 system more desirable for some wayside controller applications.

7.1.2 Onboard Failures

To have good availability of the onboard controller, the equipment is arranged in 1oo2 or 2oo3 configuration depending on the CBTC supplier. Despite the redundant architecture, designed for a few years of Mean Time Between Functional Failures, the industry survey revealed that the most frequent failure of a CBTC system comes from the onboard equipment. Understandably, there is a scale factor because there is more onboard equipment than any other CBTC equipment. However, without considering the scale factor, the onboard equipment is subject to more frequent failures than wayside ones. It is a direct result of its environment: onboard controllers are subject to vibration, wide temperature variation, dirt/dust, humidity and electromagnetic interference.

In addition to the harsh environment of the onboard controller hardware, it is a complex system including not only the main controller but also other subsystems like a speed measurement system and a communications system. In addition to hardware failures, the equipment is subject to software errors due to the complexity of the calculations and to other functional failures when the speed measurement system or the communications system suffers a malfunction or the interface between those subsystems is not working properly.

A momentary wayside failure such as loss of network communications and certain train operation errors may result in the inability for the train to continue to operate in CBTC mode. Though technically not an onboard controller failure, the impact of such an event is that the train cannot operate in CBTC, acting like a train with CBTC failure.

When an onboard controller stops, whether it can recover immediately or not, the train is unable to move in CBTC until an initialization process takes place. The initialization process is different on every project, but it always involves moving in non-CBTC mode for a short distance to localize the train. Note that there are a few projects with specific assumptions regarding the presence of non-equipped trains, plus particular train tracking and localization functions, where it is possible that a CBTC train can move immediately in CBTC mode after onboard equipment boot-up.

<u>Managing a single train with CBTC failure in CBTC project Category 1.A: Secondary System capable of revenue service</u>

- Train is switched to operate without the CBTC system in restricted speed mode until the next signal, and then either it can recover and resume CBTC operation or it is driven at restricted speed to a siding area or it is switched to bypass mode, to be able to run at a speed compatible with revenue service.
- If the following train is close to the train with CBTC failure, the following train is stopped and needs to run in non-CBTC mode for a short distance. If not close to the train with CBTC failure, the following train remains in CBTC mode and follows the train with CBTC failure, increasing the train separation but still compatible with peak or off-peak revenue service.
- Revenue service can continue with peak (Category 1.A.1) or off-peak (Category 1.A.2) performance even in the area of the train with CBTC failure.

<u>Managing a single train with CBTC failure in CBTC project Category 1.B: Secondary System designed to handle a single non-CBTC train</u>

- Train is switched to operate without the CBTC system in restricted speed mode until the next signal, for project with signals, and then, if STD/PS allows (when Categories 1.B.1 and 1.A.2 are equivalent), to bypass mode to be able to run at a speed compatible with revenue service. For projects without signals, the train remains in restricted speed mode until it is taken off the mainline or until it can recover.
- If the surrounding trains are in the same block as the train with CBTC failure, the impact on those surrounding trains depends on the CBTC system and on the layout of secondary detection devices. Some CBTC systems stop all trains surrounding the train with CBTC failure in the same interstation while other systems stop only the following train. For systems, which stop all surrounding trains, the result may be a major service disruption depending on the number of trains affected. For CBTC projects which stop only the following trains:
  - Where there are many detection devices: usually the case when track circuits are used, then like for projects in Category 1.A, if close to the train with CBTC failure, the following train is stopped and needs to run in non-CBTC mode for a short distance. If not close to the train with CBTC failure, the following train remains in CBTC mode and follows the train with CBTC failure.
  - Where there are only few detection devices: usually the case with axle counters which may have only one detection block in between two stations, the following train is stopped and needs to run in non-CBTC mode until the next station or the next detection device boundary, whichever is the closest.
- For projects with secondary detection system everywhere (Category 1.B.1, 1.B.2.1 and 1.B.3), there are only minor differences between management of a single train with CBTC failure. The main difference is the distance the train with CBTC failure and the trains affected by the train with CBTC failure need to travel to resume CBTC operation.
- For projects with secondary detection system only at interlockings (Category 1.B.2.2), the area where the surrounding trains are affected is much larger, and distance to travel before resuming CBTC operation is also longer than in other project categories.

Managing a single train with CBTC failure in CBTC project Category 2: No STD/PS

- Train is switched to operate without the CBTC system in restricted speed mode.
- The area where the train with CBTC failure is located is blocked for CBTC operation. The train with CBTC failure needs to be removed from the mainline and brought to a CBTC system initialization point, if capable of resuming CBTC operation. Another train, with full CBTC capabilities, must run in manual mode to sweep the area before CBTC revenue service can resume in the area. The result is a major service disruption.

7.1.3 Wayside Failures

7.1.3.1 Possible CBTC Train Operation During System Failures

When the wayside system fails and the onboard controller does not receive a train movement authority, the train may need to switch to a control mode where the speed is limited to a fixed low speed (may be a function of the Rolling Stock or of the CBTC system), or it may be switched to allow total control of the train by the driver, without any fixed low speed restriction.

With a wayside failure, the transit agency may still want to benefit from having the onboard equipment, which is still functioning. Localization of the train is strictly an onboard function and once established it continues to be available even when isolated from the rest of the CBTC system. Therefore, it is possible that the onboard controller continues to enforce the civil speed and possibly any temporary speed restriction which was already memorized by the onboard controller. This mode of operation is only efficient when an STD/PS is present, otherwise the restricted speed must be enforced. An issue faced in this mode is the determination of the speed to enforce over track switches which may be different depending on the position of the switch. This information must be communicated to the train from the wayside or else the minimum speed is chosen. Alternatively, it may be decided that civil speed is not enforced in the track switch areas.

7.1.3.2 Wayside Controller Failures

Wayside controllers can manage the entire line or a portion of the mainline territory, usually covering a few interstations. Though the equipment always includes redundancy and is designed for a Mean Time Between Functional Failures of several years, it is subject to failures which can be a direct result of the equipment hardware failure or software crash or an indirect failure, like loss of power in the technical room.

A wayside controller failure results in the inability of the transit agency to operate trains in CBTC mode in the area managed by the failed equipment. All trains in the territory are brought to a stop.

Wayside controllers are arranged in 1oo2, two redundant 2oo2, or 2oo3 configuration to have the best availability possible.

Managing a wayside controller failure in CBTC project Category 1.A: Secondary System capable of revenue service

- All trains are switched to operate without the CBTC system in restricted speed mode until the next signal, and then to bypass mode to be able to run at a speed compatible with revenue service.
- Revenue service can continue with peak (Category 1.A.1) or off-peak (Category 1.A.2) performance in areas inside the failed control zone. Normal operation is possible in areas outside the failed control zone.
- After the wayside equipment is fixed and in operation, and communication is established with the train onboard equipment, CBTC operation can restart.

Managing a wayside controller failure in CBTC project Category 1.B: Secondary System designed to handle a single non-CBTC train,

- All trains are switched to operate without the CBTC system in restricted speed mode.
- In projects of Category 1.B.1, revenue service can continue with absolute block operation, one train per block, a block usually covering an interstation. Speed is limited. Normal operation is possible in areas outside the failed control zone.
- In projects of Categories 1.B.2 and 1.B.3, no level of revenue service is possible. Trains are usually moved at restricted speed up to the platforms and wait until the zone is fixed.
- After the wayside equipment is fixed and in operation, and communication is established with the train onboard equipment, CBTC operation can restart.

Managing a wayside controller failure in CBTC project Category 2: No STD/PS

- All trains are switched to restricted speed mode where they can operate without the CBTC system.
- Trains are kept at a stop until the failure is fixed or move at slow speed up to the station for unloading passengers.
- Revenue service is not possible in the affected area. Normal operation is possible in areas outside the failed control zone.
- After the wayside equipment is fixed and in operation, major operating procedures are necessary to restart CBTC operation.

Recovery from a wayside controller failure

Due to the important consequences of wayside controller failures in some of the CBTC projects, there has been work by suppliers and transit agencies to include functions which allow restart of the trains without having to re-initialize each train, provided specific conditions are met. The function makes use of the train localization which is maintained by the onboard controller while the wayside controller is failed. After the reboot of the wayside controller, provided all train localization messages are received by the wayside controller and possibly other conditions, CBTC operation may restart immediately.

7.1.3.3 Issue of Equipment Centralization

There are two solutions regarding the location of the wayside controller.

Decentralized wayside controller:

Wayside controllers are in the technical rooms near the area they manage. This may be a requirement where controllers need access to the local relay-based circuits with which they interface, such as for overriding STD/PS.

Cons:
- The technical room environment may be more demanding than a centralized facility, like the control center.
- Access is more complicated than if all were centralized in a place easily reached by maintenance.

Pros:
- It avoids complete line failure since each controller is isolated from the others.

Centralized wayside controller:

Thanks to a communications network, all wayside controllers are located in a single technical room.

Cons:
- May need remote Input/Output interface equipment in the technical rooms.

- Prone to a failure of the entire line, for instance in case of loss of power to the room.

Pros:

- Easily accessible by maintenance.

When centralized, it is common that the wayside controllers are duplicated in a back-up location. The back-up wayside controllers are turned off during normal operation and ready to be booted up in case of a problem at the primary location.

With the early deployments of CBTC, most wayside controllers were located near the area they managed. Centralization of controllers is a recent practice.

7.1.3.4 Automatic Train Supervision System Failures

Technically, CBTC operation is possible without ATS systems, even for driverless projects where the trains can continue under certain conditions.

The transit agency may continue operation during ATS failures or may decide to stop revenue service. Since ATS controls the entire line, where the transit agency decides not to operate trains during an ATS failure, the consequences are major.

Recovery of an ATS failure may involve many control center actions, but it can be done locally in the control center without requiring any specific train movement.

ATS servers may be arranged in a 1oo2 configuration and each unit may be in a different location. Sometimes multiple locations will have a 1oo2 configuration (four units in total) and one location is a back-up of the main control center.

7.1.3.5 Network Communications Failures

Communications network failures may result in loss of part or all of the ability to run in CBTC mode. Communications failures are highly dependent on the type of network architecture used in the project but they may be summarized in the following categories:

- Radio communications failure, which results in the loss of communication between the onboard controller and the wayside controller, may come from:
    - Problems with the onboard controller – the result is the same as having a single train with CBTC failure.
    - Problems with the radio access point: radio access points receive information through the network and provide it to the onboard controller via the radio. There is usually coverage redundancy between two or more antennas, so a problem with a single access point should not result in any loss of functionality. Where the coverage redundancy is missing or several consecutive access points are failed, CBTC operation over the area without radio coverage is not possible. Consequences are similar to a failed wayside controller.
    - A network failure where the communication between the access point and the wayside controller is not available.
- Wayside network communications failures (which may induce a radio communications failure) also result in CBTC operation failure over the area where communication is out of service. Operation is the same as when a wayside controller fails, however the area affected may be smaller.

  Network failures can also stop the communication between wayside controllers which would result in failure of the CBTC trains to be handed over from one Zone Controller to another. The operational issues depend on the implementation of the handover zones and should be evaluated for each project.

In projects using processor-based interlockings, and where the interface between the interlocking and the wayside controller is digital, then loss of communication between an interlocking and the wayside controller results in an inability to continue CBTC operation over the area controlled by the interlocking.

7.2 STD/PS Equipment Failures

It is very important to note that when a secondary system is used, it is implemented such that its detection and protection functions are active and interface with the CBTC system at all times. Therefore, any failure of the secondary system has the potential to impact the performance of the CBTC system. This section presents some of the possible secondary system failures and the impact on CBTC operation.

7.2.1 Track Circuit Failures

A track circuit is a fail-safe solution and, when failed, it reports as if it were occupied by a train. The CBTC can detect that a track circuit is failed by comparing the localization of the trains and the track circuit status. For instance, if a track circuit which is not occupied by any train suddenly reports occupied, then the wayside controller determines that it is due to a failure of the equipment and not due to a train present on the track circuit and shunting the running rails.

When a track circuit is detected as failed, CBTC trains may be impacted. Trains may be required to stop and switch to a restricted CBTC mode or non-CBTC mode of operation before entering the track circuit block. Alternatively, there might be relatively complex CBTC functions which allow continued CBTC operation over the area, where the function may be automatic or may require ATS operator intervention.

In most projects, the CBTC system uses the determination that the track circuit is failed to allow CBTC operation over it. Authorizing CBTC operation over the area may be automatic or may require a control center ATS command. Because the track circuit failure may be due to a broken rail, a slow speed may be enforced while the train is occupying the track circuit. Depending on the option chosen by the transit agency, a track circuit failure may be transparent for CBTC operation.

The rare and unsafe case of a failed track circuit in the vacant state, even when a train is shunting the rails, is handled by CBTC, inhibiting train operation in CBTC mode.

Recovery:

After the track circuit is repaired, CBTC operation may resume immediately over it. A control center ATS command may be necessary to remove the restrictions on operation depending on the type of failure and the agency procedures.

7.2.2 Axle Counter Failures

Failure of an axle counter impacts the blocks before and after the axle counter. Similar to a failed track circuit, the axle counter output is used by CBTC at all times, and therefore CBTC trains may be stopped before entering the blocks around the failed axle counter.

As for the track circuit, in most projects, the CBTC system uses the determination that the axle counter is failed to allow CBTC operation over the area. Authorizing CBTC operation may be automatic or may require a control center ATS command to disregard the failed axle counter. Depending on the option chosen by the transit agency, an axle counter failure may be transparent for CBTC operation.

Recovery:

Unlike track circuits, returning to normal operation after an axle counter failure requires a process to verify that the blocks around the repaired axle counters are empty. The procedure can be:

- Sweeping the area with a train.
- Sending a command to the axle counter system after verification that the blocks are empty. The verification usually involves having personnel in the field.
- Using train tracking from the wayside controller, CBTC may identify the axle counter failures. In this case, it may automatically authorize operation over the area and reset the axle counter.

7.2.3 Stop Enforcement Devices and Signal Failures

Section 5.3, STD/PS Implementation, describes the possible integration of the STD/PS in the overall signaling system. In certain cases, the stop enforcement of the secondary system is active for all trains and needs to be overridden by the CBTC system. Similarly, the transit agency may want to override signal aspects to avoid having CBTC trains pass restrictive signals. In those cases, failure of the enforcement devices or of the signal results in the inability to run CBTC trains over the area. To mitigate the impact of those failures, transit agencies usually develop functions that can manage field device failures.

In addition to the complexity of having an interface between the secondary system and the CBTC system, the failure management is often very sophisticated and could lead to numerous hours of design and testing.

Example of mitigation of signal failures:

When a signal fails to clear, a control center ATS command may be used to command the CBTC system to disregard the failed equipment and CBTC operation may continue. CBTC operation may be at low speed or at normal speed. Recovering from the situation after the failure has been repaired may be automatic or may also require a command from the control center.

7.2.4 Processor-Based Interlocking Failures

In relay-based circuits, the failure of one relay is very localized and may affect one signal, one switch, or a particular route. Failure management is then similar to the single equipment failure management described in previous sections.

However, when a processor-based interlocking contains logic for an entire interlocking and/or portions of automatic block territory in one chassis, then CBTC operation is not possible over the entire area controlled by the failed processor. It is not possible to manage an entire area like several single equipment failure devices. For this reason, processor-based interlockings are usually arranged in a hot standby redundant configuration. Recovery of a complete processor failure does not involve any particular function, but may rely on operating procedures for the trains present in the area controlled by the processor.

SECTION 8

Work Trains

Work trains are defined as maintenance vehicles used by the transit agencies to perform inspections or maintenance of the railroad infrastructure.

The management of work trains is driven by different factors such as the age of the infrastructure, whether the revenue service is stopped overnight, and whether work trains need to run in between revenue service CBTC trains. Another factor is the current experience of the transit agency; a transit agency with a cab signaling system that has few signals or signals only at interlockings is already used to managing non-equipped work trains.

Equipping work trains is a difficult challenge because of the sheer number and variety of work trains. Fitting CBTC equipment on a train is a considerable investment. The different options, benefits, and consequences are presented in the following sections.

In this document it should be understood that work trains are trains capable of being detected by the secondary detection system. Where maintenance equipment, such as hi-rail vehicles, may not have steel wheel shunting sufficient for use by track circuits, or may not be able to be detected by wheel sensors for axle counters, following operating rules is the only alternative for CBTC projects. Equipping hi-rail vehicles, for example, would be a tremendous customization effort generally not worth the investment.

8.1 Not Equipping Work Trains

One option is to not equip the work trains at all. Management of the work trains depends on the type of secondary system, where Categories 1.A and 1.B.1 can manage work trains entirely on the signaling system without relying on operating procedures. Categories 1.B.2 and 1.B.3 can manage work trains using a mix of the signaling system and some operating procedures, while Category 2 relies completely on operating procedures.

Table 6: Not Equipping Work Trains

Type	Category	Sub-category	*Not equipping work trains*
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**	
	1.A.1	Secondary System capable of peak revenue service	Fully supported by the signaling system
	1.A.2	Secondary System capable of off-peak revenue service	Fully supported by the signaling system
	1.B	**Secondary System designed to handle a single non-CBTC train**	
	1.B.1	Capable of one train per interstation	Fully supported by the signaling system
	1.B.2	Capable of one train in between two interlockings	
	1.B.2.1	With secondary detection method everywhere	Relying partially on the signaling system and partially on operating procedures; Procedures are facilitated by the knowledge of the location of the train

Type	Category	Sub-category	*Not equipping work trains*
	1.B.2.2	With secondary detection method only at interlocking	Relying partially on the signaling system and partially on operating procedures
	1.B.3	Without territory specific headway performance	Relying on operating procedures facilitated by the knowledge of the location of the train
Systems without STD/PS	**2**	**No Secondary System**	Entirely relying on procedure

The 1.B.2 Category is divided into 2 subcategories, 1.B.2.1 with detection devices everywhere, and 1.B.2.2 with detection devices only at interlockings. One of the reasons for having detection devices everywhere as in 1.B.2.1 and 1.B.3 is to be able to detect non-equipped trains with finer resolution. By having detection of non-equipped trains, CBTC can provide protection for those trains with smaller separation.

8.2 Equipping Work Trains

It is technically possible to equip the work trains with CBTC. Each type of vehicle is fitted with an onboard controller adapted for the type of vehicle. Customization of the onboard equipment to fit and function properly on a work train requires a major design effort and may not be possible for the number of different types of work trains. The customization must be done for each type of work train. Major elements of this work include fitting the onboard controller in the work train, routing cables between controller and other components and sensors, developing interfaces with propulsion and braking systems, mounting transponder reader and speed sensors, designing and preparing drawings, testing, and post-implementation modifications.

To simplify integrating the onboard controller on the work train, it is possible that the onboard controller is implemented such that it has no control of the vehicle and thus no enforcement of speed or movement authority limit. In this case, the onboard controller only reports location of the trains to the wayside controller which provides protection from other CBTC trains and possibly some interlocking protection as well.

Another possible mitigation is to equip only part of the work train fleet or only the locomotives that pull or push work cars. This avoids heavy investment of equipping all work trains but allows having CBTC protection for most of the work trains. Since only one extremity of the work consist may be equipped, neither the onboard equipment nor the wayside controller knows the length of the work train and assumptions must be made for front- and rear-end protection.

The industry survey showed that there appears to be no relation between equipping work trains and the category of CBTC project. Some CBTC projects with off-peak performance (Category 1.A.2) have fully equipped some of their work trains, though those trains could be run without CBTC with minimal impact in revenue service. On the other hand, agencies with no STD/PS but with night closure, have decided to not equip the work trains at all. The influence of the night closure is more important than the capability of the secondary system.

8.3 Using a CBTC Equipped Trailer

To avoid equipped maintenance vehicles, some transit agencies use a trailer equipped with CBTC which is then attached to the maintenance vehicle. The trailer reports location of one end of the consist to the wayside controller which provides protection from other CBTC trains and possibly some interlocking protection as well, such as locking switches based on the location of the trailer and its vehicle. This option is described in Case Study 1, AirTrain JFK.

8.4 Using a Separate Tracking System

As discussed in previous options, locating the maintenance vehicles is a major concern for transit agencies. Considering that work trains usually operate at low speed, there may not be a need to have the complete CBTC ATP functions active, where the continuous speed control is not necessary for trains already running at low speed. However, protection of the work train from other CBTC revenue service is important and is possible only by knowing the work train location. Therefore, it is possible to use other creative methods of train localization integrated with the CBTC system to allow protection from other trains. These creative methods may be using Radio Frequency Identification (RFID) or a Global Navigation Satellite System (GNSS), such as the United States Global Positioning System (GPS), for outdoor areas. Protection of the work train could be automatic if the tracking system is linked to CBTC or manually performed by the ATS operator knowing the location of the work train by the separate tracking system. Only a few projects have used such methods. Though their level of safety is lower than track circuit and axle counter, this is a possibility worth mentioning.

8.5 Minimum Non-Equipped Train Length Issue

The train length topic results in different issues:

- Train length needs to be determined to provide some or all of the CBTC protections. For instance, if a trailer or a CBTC equipped locomotive is used, the train length must be known. Train length may be:
    - Assumed to be the maximum possible length for a work train
    - Captured by an operator and input into the CBTC system
    - Determined by the CBTC system automatically, for instance using axle counters
- For projects in Categories 1, the train initialization process into the CBTC system needs an assumption regarding the minimum non-equipped train length. This assumption is used by the wayside controller to confirm that there is no non-equipped train in front of the CBTC train before calculating the movement authority limit. The longer the minimum train length, the easier it is for the wayside controller to determine that there is no non-equipped train between the CBTC equipped trains. The main impact is the maximum speed at which the determination may happen. The principle involves calculating the difference between the location of the front of the train to the next vacant track circuit or axle counter block. If this difference is smaller than the minimum length of a non-equipped train, then the wayside controller can conclude that there is no non-equipped train in front of the initializing train. For projects in Categories 1, this issue is important because performance of train initialization in the system, especially after a system failure, impacts how quickly the train can resume CBTC operation.

8.6 CBTC Work Zone Function

CBTC systems include a function to enhance safety of roadway workers at work sites. This function can create a restriction on the mode of operations and/or speed of CBTC trains in a particular area of the track. The restriction can be, for instance, to inhibit automatic mode operation. Because not all trains might be CBTC trains, other protections in the field such as flags and lanterns are still used.

This function provides protection for a specific zone which is captured at the control center on the ATS system. Though it is a powerful function, it does not solve the problem of transferring the work train from the storage area to the work site and then back to the storage area. Work Zones may be set based on train movement, blocking an entire area when the train is moving based on location reported by the crew on the work train, but it is not practical since it requires a lot of coordination between the crew and the control center.

Similar to the Work Zone function, the CBTC system includes a function that limits only the speed of CBTC trains over a specified area. This is usually used in cases of degraded track conditions or on tracks adjacent to work zones.

SECTION 9

CBTC Category Selection Process

9.1 Summary of Previous Sections

The following table summarizes the differences among the project categories.

Table 7: Summary of Functions by Category

Category	Type	Possible back-up for revenue service	Support mixed-fleet to facilitate cut-over	Manage a single train with CBTC failure	Manage work trains	Drawbacks on deployment, maintenance, and CBTC operation availability
1.A	**Secondary System capable of revenue service**					
1.A.1	**Secondary System capable of peak revenue service**	Yes	Yes	Yes	Yes	Major
1.A.2	**Secondary System capable of off-peak revenue service**	Yes, with performance degradation	Yes, with phased implementation	Yes	Yes	Major
1.B	**Secondary System designed to handle a single non-CBTC train**					
1.B.1	**Capable of one train per interstation**	Yes, with performance degradation	No	Yes	Yes	Moderate
1.B.2	**Capable of one train in between two interlockings**	Not likely, but depends on the layout and off-peak performance	No	Yes, but operating procedures needed	Yes, but operating procedures needed	Minor to moderate
1.B.2.1	**With detection devices everywhere**	Not likely, but depends on the layout and off-peak performance	No	Yes, but operating procedures needed. Procedures facilitated by knowledge of location of the train	Yes, but operating procedures needed. Procedures facilitated by knowledge of location of the train	Moderate
1.B.2.2	**With detection devices only at interlocking**	Not likely, but depends on the layout and off-peak performance	No	Yes, but operating procedures needed	Yes, but operating procedures needed	Minor

Category	Type	Possible back-up for revenue service	Support mixed-fleet to facilitate cut-over	Manage a single train with CBTC failure	Manage work trains	Drawbacks on deployment, maintenance, and CBTC operation availability
1.B.3	**Without territory specific headway performance**	Not likely, but depends on the layout and off-peak performance	No	Yes, but operating procedures needed. Procedures facilitated by knowledge of location of the train	Yes, but operating procedures needed. Procedures facilitated by knowledge of location of the train	Moderate
2	**No secondary system**	No	No	Only by operating procedure	Only by operating procedure	None

9.2 Selection Criteria

This section presents the various factors to be considered when evaluating the possible secondary systems appropriate for a specific transit agency. Selection of these factors was based primarily on the industry survey.

These factors are driven by the following needs:

1. Mixed-fleet operation during the cut-over to CBTC
2. Using the STD/PS as a back-up system:
    a. Operation at peak headway with the secondary system
    b. Operation at off-peak headway with the secondary system
    c. Management of a single train with CBTC failure using the secondary system
3. Handling of unequipped work trains
4. Detection of broken rail by the signal system

9.2.1 Mixed-fleet Operation During the Cut-Over to CBTC

The need for a mixed-fleet operation depends greatly on the type of legacy train control system as well as the rolling stock in service. It is common that the cut-over to CBTC impacts the type of STD/PS used on the project, at least temporarily. Considering the life duration of the CBTC system, at minimum 30 years, having the cut-over strategy impact the choice of the permanent secondary system should be avoided.

Dual equipping the wayside – both legacy system and CBTC system

It is not always feasible to avoid the issue of having the cut-over impose the need for STD/PS due to the constraints listed below:

- Implementation is a brownfield project – current revenue operation cannot be disrupted
- Only new trains are delivered with CBTC equipment or CBTC ready
- Legacy trains are needed to make up the minimum fleet required for revenue service, but will not be equipped with CBTC

- The new trains cannot use the legacy train control system to operate at a headway sufficient for revenue service. For instance, this is the case when the new trains cannot be equipped with the legacy system onboard equipment.

Examples:

- In a transformation to a CBTC driverless system, new trains are equipped with CBTC, while legacy trains, not equipped with CBTC, continue to provide revenue service. It is generally impractical to retrofit old trains with CBTC. In this case, the need for mixed-fleet operation results in the selection of Category 1.A, an STD/PS capable of revenue service.
- Another case is when not all trains are able to run in CBTC mode at the beginning of CBTC operation, irrespective of whether the new or upgraded trains can run on the legacy system. For example, Case Study 3 – NYCT's first project, the Canarsie Line, did not have sufficient CBTC-ready trains at the beginning of the project, so a mixed-fleet operation was needed to meet service demands.

This section emphasizes the importance of coordination between the new train procurement or the train upgrade and the signaling project.

<u>Dual equipping the train – train may run under CBTC and under legacy system</u>

There is a possibility that the cut-over strategy has no impact on the STD/PS. Provided all trains are equipped with CBTC at the beginning of CBTC revenue service, and that they can operate on the legacy signaling system as well, it is possible to start CBTC revenue service on part of the line or on the entire line without having the need for mixed-fleet operation. This case provides the agency with the possibility to choose the appropriate level of STD/PS, if any is needed. From the industry survey, no brownfield project has implemented CBTC without STD/PS; however, provided all trains are equipped with CBTC before revenue service, this option is possible.

Table 8: Meeting the Need for a Mixed-Fleet Operation

Type	Category	Type	*Need for a mixed-fleet operation*
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**	
	1.A.1	Secondary System capable of peak revenue service	✓
	1.A.2	Secondary System capable of off-peak revenue service	✓*
	1.B	**Secondary System designed to handle a single non-CBTC train**	
	1.B.1	Capable of one train per interstation	
	1.B.2	Capable of one train in between two interlockings	
	1.B.3	Without territory specific headway performance	
Systems without STD/PS	**2**	**No Secondary System**	

*It is possible to start CBTC operation with a secondary system capable of peak performance, and subsequently reduce it to off-peak performance to maximize the benefits of the CBTC technology. This strategy has been used by NYCT as described in Case Study 3, where the project started in Category 1.A.1 for a period of time, until all trains were capable of CBTC and the system was operationally stable, and then reduced the amount of wayside equipment to cut-over the system into a project of Category 1.A.2.

Starting with a Category 1.A.1 and going to a Category 1.B would require a large amount of effort and no such project could be found during the industry survey. This is technically feasible, provided that the legacy system is used as the secondary system temporarily. This option is discussed further in Section 9.3.2 Revisiting the Cut-over Strategy.

9.2.2 Using the STD/PS as a Back-up

The reason for implementing STD/PS is often to use it as a back-up system in case of CBTC failures, either wayside controller or train-borne controller failure. Transit agencies may require a back-up for the following reasons:

First category of reasons is due to perception of the CBTC technology:

- CBTC technology has not been commonly used in North America so far and though it is a proven technology with over 30 years of successful experience around the world, transit agencies in North America may still see it incorrectly as emerging.
- CBTC relies heavily on electronic equipment, unlike some conventional signaling systems, and the technology gap between conventional signaling and CBTC may be too large for a transit agency to feel comfortable to depart from its legacy principles.

The second category of reasons are the drawbacks of the CBTC technology benefits:

- One of the advantages of CBTC is to be able to perform with less equipment; but on the other hand, failure of any equipment is more critical than in other signaling systems. Unlike conventional signaling systems and other advanced systems such as cab signaling where failure of equipment is localized in the small area governed by the equipment, CBTC is more centralized and some of the failures may affect a large geographical zone. For instance, failure of a wayside controller affects the entire zone which may be several interstations, or failure of the data communications network system may affect the entire line.
- CBTC technology provides many functionalities, allowing flexible operation, and therefore it is a complex system. Deployment is more difficult than other signaling systems. Once a conventional or cab signaling system is placed in service, there are a limited number of failures, while CBTC systems take time to become stable. Simpler systems have simpler failure modes: the consequences of a relay failure are predictable while the consequences of a software timing issue, for example, are probably not (just localizing a failure to a software timing issue requires a large effort). One of the reasons for CBTC system complexity is the use of a secondary system and the interface needed between CBTC and the secondary system. So, the secondary system itself is adding to the problem which it is trying to solve.

A possible method to evaluate whether the appropriate level of STD/PS has been selected is to perform a hazard risk assessment, specifically addressing train collision and derailment hazards, for trains not running under CBTC protection.

9.2.2.1 Operation at Peak Headway with the STD/PS

Based on the industry survey, the only time there was a permanent need to run peak headway using the secondary system was when trains from lines other than the CBTC equipped line had to operate through the CBTC territory.

This case is very particular and it is possible, as described in the Case Study 3 – NYCT Canarsie Line, that only part of the line used for such transfer is equipped with a secondary system capable of peak performance.

Further considerations

An STD/PS capable of peak headway may be under consideration for brownfield projects, where the reason for deploying CBTC is only for continuous speed control. In this case, to simplify implementation of the CBTC system, the new CBTC is overlaid on top of the existing conventional signaling system. All other benefits of CBTC technology may be constrained by the underlying secondary system, especially the capacity increase, but the transition to CBTC is greatly simplified.

Table 9: Meeting the Need to Operate a Peak Headway with the Secondary System

Type	Category	Type	*Need for a peak headway*
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**	
	1.A.1	Secondary System capable of peak revenue service	✓
	1.A.2	Secondary System capable of off-peak revenue service	
	1.B	**Secondary System designed to handle a single non-CBTC train**	
	1.B.1	Capable of one train per interstation	
	1.B.2	Capable of one train in between two interlockings	
	1.B.3	Without territory specific headway performance	
Systems without STD/PS	**2**	**No Secondary System**	

9.2.2.2 Operation at Off-Peak Headway with STD/PS

This need is based on whether an off-peak revenue service is necessary in case of major CBTC system failure.

From the industry survey, an STD/PS capable of off-peak revenue service is deemed necessary for brownfield projects that have a high capacity demand with few or no alternative transportation modes and require other considerations such as crowd control on the platforms.

Further considerations

Though technically possible for greenfield projects, the industry survey did not identify any CBTC greenfield projects where a STD/PS capable of peak or off-peak performance was selected.

Table 10: Meeting the Need for Back-up for Revenue Service

Type	Category	Type	*Need for back-up for revenue service*
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**	
	1.A.1	Secondary System capable of peak revenue service	✓* (possible but unnecessary)
	1.A.2	Secondary System capable of off-peak revenue service	✓
	1.B	**Secondary System designed to handle a single non-CBTC train**	
	1.B.1	Capable of one train per interstation	
	1.B.2	Capable of one train in between two interlockings	
	1.B.3	Without territory specific headway performance	
Systems without STD/PS	**2**	**No Secondary System**	

*Category 1.A.1 can provide back-up for revenue service since it is capable of peak revenue service operation, but it may be unnecessary.

9.2.2.3 Management of a Single Train With CBTC Failure Using the STD/PS

A scenario similar to the mixed-fleet operation is the management of a single train with CBTC failure. This is akin to the question of how to handle work trains, but since mitigations are possible for the work trains, the two issues are addressed separately. Also, the category of projects for managing a single train with CBTC failure and for work trains might be different.

Based on industry survey responses, the most frequent failure of the CBTC system is the onboard train equipment.

For systems with high capacity demand and service, the recovery strategy mandates that managing a train with CBTC failure and moving it out of the system is important. A single train with CBTC failure not only creates revenue service disruption for the failed train, but also for several other following trains, creating a much more difficult situation to handle.

Table 11: Meeting the Need to Manage a Single Train with CBTC Failure with the Secondary System

Type	Category	Type	*Manage a single train with CBTC failure*
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**	
	1.A.1	Secondary System capable of peak revenue service	✓ (possible but unnecessary)
	1.A.2	Secondary System capable of off-peak revenue service	✓ (possible but unnecessary)
	1.B	**Secondary System designed to handle a single non-CBTC train**	
	1.B.1	Capable of one train per interstation	✓
	1.B.2	Capable of one train in between two interlockings	✓ (Only for 1.B.2.1)
	1.B.2.1	With detection devices everywhere	✓ Protection around the train with CBTC failure
	1.B.2.2	With detection devices only at interlocking	
	1.B.3	Without territory specific headway performance	Protection around the train with CBTC failure
Systems without STD/PS	**2**	**No Secondary System**	

9.2.3 Handling of Unequipped Work Trains

Depending on the needs assessment for an STD/PS, the necessity for a mixed-fleet operation, and the need to manage trains with CBTC failure, the management of unequipped work trains may have already been included by default. If the selection did not include any previous solution categories, then the work train management needs to be addressed. Usually, work trains are used in a particular area which can be protected by operating rules; however, the main issue is in the movement of the train from the storage area to the work site and then back to the storage area when the work is finished. A similar issue arises with the use of a track inspection or geometry car, for example, that traverses large portions of the mainline. Section 8 – Work Trains, presents the various options regarding the management of work trains. There are two categories: 1) using procedures and not equipping work trains and 2) equipping work trains to an appropriate level to provide some level of protection.

Not equipping work trains may be considered reasonable when:

- The STD/PS already can manage revenue operation at peak headway (Category 1.A.1)
- A back-up for revenue service is already selected (Category 1.A.2)
- The STD/PS already handles a single train with CBTC failure (Category 1.B)

Unequipped work trains result in impacts on revenue service where:

- There is only interlocking protection by the STD/PS. In this case, depending on the line layout and separation of the interlockings, running unequipped work trains may seriously impact revenue service.

- There is no STD/PS (Category 2). In this case, non-equipped work trains are managed entirely by operating procedure.

Where transit agencies do not operate revenue service 24/7, maintenance work is typically performed during the nightly system closure, and unequipped work trains have no negative impact on revenue service. The agency must rely on operating procedures for safe movement during the closures.

Equipping work trains is highly recommended when both of these conditions exist:

- The system operates 24/7 and work trains would have to be routed in between revenue service trains. Relying on operating procedure would dramatically impede revenue service and the operating procedures would require a lot of coordination effort.

And

- There is no STD/PS that can facilitate tracking and/or control of the trains.

Section 8 – Work Trains, presents different options for equipping work trains resulting in various levels of work train protection. The choice is dependent on the transit system's characteristics, such as the number and type of work trains, and the CBTC or STD/PS supplier's technology. This guide only addresses the needs assessment for an STD/PS and whether to equip work trains, and not how to equip them or what level of protection to provide.

Table 12: Work Train Management by Category

Type	Category	Type	Equipping work trains
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**	
	1.A.1	Secondary System capable of peak revenue service	Not required
	1.A.2	Secondary System capable of off-peak revenue service	Not required
	1.B	**Secondary System designed to handle a single non-CBTC train**	
	1.B.1	Capable of one train per interstation	Not required
	1.B.2	Capable of one train in between two interlockings	Depends on layout and if operation is 24/7
	1.B.3	Without territory specific headway performance	Depends on layout and if operation is 24/7
Systems without STD/PS	**2**	**No Secondary System**	Only if operation is 24/7

9.2.4 Detection of Broken Rail by the Signal System

There are two ways to view the broken rail issue and its effect on STD/PS decision making:

- One way is to consider the broken rail detection feature of track circuits as a mandatory requirement for the choice of a secondary system in a CBTC project. This traditional approach of determining the method of secondary detection before choosing the level of secondary protection in a CBTC system defaults to keeping the track circuits, often resulting in project Category 1.A.
- Another way is to consider the type of secondary system needed from a functional point of view, and if a secondary system is needed, then decide on a detection method—track circuits or axle counters—that meets the needs of the project. This is the approach proposed in this guide. Section

9 – CBTC Category Selection Process, proposes a decision-making method to evaluate the need for a secondary system, and Section 10 – Choosing the Secondary Method of Detection, presents a decision-making method to evaluate the type of secondary train detection equipment.

Broken rail detection has been widely perceived as an important feature in the application of track circuits, though it is not the primary function of a track circuit. However, its efficacy has been questioned, as noted in American Public Transportation Association (APTA) standard RT-FS-S-002-02, "Rail Transit Track Inspection and Maintenance," where it has been documented that "signal circuits do not provide 100 percent reliability for pull-apart detection." Given that broken rails are a serious risk for train operation, agencies need to proactively detect rail flaws before the rail completely breaks.

Broken rail detection with track circuits can only be effective when a track circuit is known to be vacant. That is, a broken rail is masked if there is a train occupying the track circuit. Under CBTC, especially during peak periods, trains are closely spaced and may be occupying most track circuits, rendering such broken rail detection ineffective. Effectiveness of broken rail detection is reduced even further with longer track circuits (such as might be found between stations or interlockings in Category 1.B) since longer track circuits are more likely to be occupied.

Furthermore, broken rail cannot be reliably detected on the negative rail of single-rail track circuits with bypaths through the traction return system; nor on running rail on the inside of curves where there is restraining rail attached to it.

Broken rail detection should not be considered as a primary decision factor in choosing the functional level of a secondary system. Rail flaw detection has been shown to be successful in CBTC projects that do not have track circuits. The industry survey revealed that several projects successfully use only inspection methods to detect rail flaws. Such examples, in Section 12 – Case Studies, include case studies of Transport for London and British Columbia Rapid Transit Company.

9.3 Decision Flow Diagrams

In summary:

- The lowest level of secondary system to meet the functional needs is the most desirable.
- Work train management is either a factor in the decision for an STD/PS or a result of the STD/PS chosen for the project. In the following flow diagrams, it is shown as a factor.
- Broken rail detection should be kept separate from the decision flow diagram.
- The type of detection equipment, track circuit or axle counter, should be kept separate from the evaluation of the level of secondary system.
- When looking at the flow diagram, transit agencies may be considering different categories of CBTC on different parts of the line where the needs may be different based on geographical areas. For instance, in Case Study 3, on the NYCT Canarsie Line project, there was a need to handle non-equipped train transfers on one part of the line but not on another. Another example may be the need to have a back-up or to handle a single train with CBTC failure in the city center where possibly several CBTC lines merge and headway requirements are crucial, but have no such needs outside of the city where capacity is less.

There are several decision processes depending on the initial factors to be considered.

9.3.1 Decision Flow Diagram

In Figure 11, Decision Flow Diagram for STD/PS Selection, greenfield projects can skip the mixed-fleet step and start with the need for peak revenue service provided by the STD/PS.

The diamonds represent a functionality of the STD/PS. The diamonds are:

- Mixed fleet during cut-over: Is mixed fleet needed during the cut-over to CBTC from the legacy train control system? See section 9.2.1 for information about making this decision.
- Peak performance permanently: Is operation at peak headway with the secondary system needed in the final system, as opposed to only during the cut-over? See section 9.2.2.1 for information about making this decision.
- Peak performance: Is operation at peak headway with the secondary system needed in the final system? See section 9.2.2.1 for information about making this decision.
- Off-peak performance: Is operation at off-peak headway with the secondary system needed in the final system? See section 9.2.2.2 for information about making this decision.
- Manage single train with CBTC failure: Is management of a single train with CBTC failure using the secondary system needed? See section 9.2.2.3 for information about making this decision.
- Manage unequipped work train: Is management of unequipped work trains using the secondary system needed? See section 9.2.3 for information about making this decision.

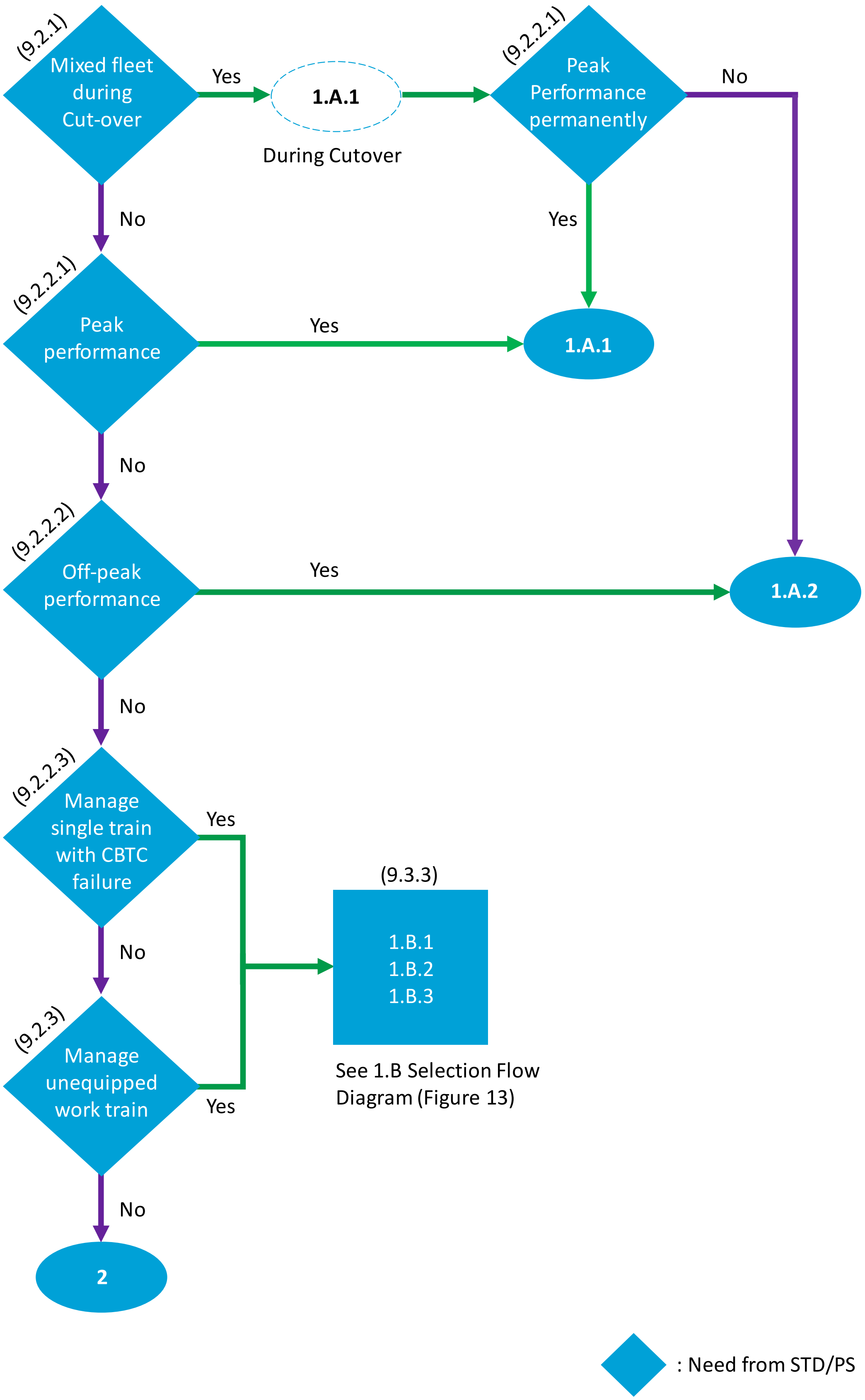


Figure 11: Decision Flow Diagram for STD/PS Selection

9.3.2 Revisiting the Cut-Over Strategy

Most of the information presented in the previous sections is based on results from the industry survey. Regarding the cut-over during the implementation of CBTC in brownfield projects, other possible cut-over methods can be considered.

For projects where mixed-fleet operation cannot be avoided, one possible method of cut-over used in project Category 1.A is to start CBTC operations with a secondary system capable of peak revenue service. Then in a second step, remove some of the secondary signal equipment to reap the benefits of CBTC, eliminating the headway restrictions imposed by the STD/PS. Based on the industry survey this was done only for projects in Category 1.A, but not for other types of projects, such as Category 1.B and 2.

Consideration should also be given to the transition process used when migrating to other categories of CBTC systems, such as 1.B or 2, where mixed-fleet is only needed during the transition to CBTC, and not in the final configuration. The transit agency can consider deploying a system capable of mixed-fleet operation (Category 1.A) followed by its decommissioning once the transition is complete, leading to Category 1.B or 2.

Two possible options include:

1. Interface with the legacy system and decommission it after the transition to CBTC. (The industry survey showed projects where the legacy system was interfaced but not decommissioned.)
2. Install a new (temporary) secondary system and decommission it after the transition to CBTC. The industry survey has not revealed any project where this method has been used yet.

In both cases, the CBTC trains may be designed to behave like the trains governed by the legacy system (the soon-to-be secondary system). This type of transition is technically possible whether the legacy system is a conventional signaling system or an automatic cab signal system.

The principal benefit of this transition is that mixed-fleet operation is facilitated, and the final project configuration is not impacted by the transition to an optimal CBTC system category.

The disadvantage is the effort to deploy the CBTC system in a Category 1.A configuration, and the effort to decommission the secondary system, partially or completely. For agencies desiring a Category 2 final solution without a secondary system, all of the secondary system has to be removed. It would therefore be preferred that the new CBTC system interface with the existing signaling system, that will then be decommissioned when all trains are CBTC equipped.

Figure 12 illustrates the adjusted Decision Flow Diagram:

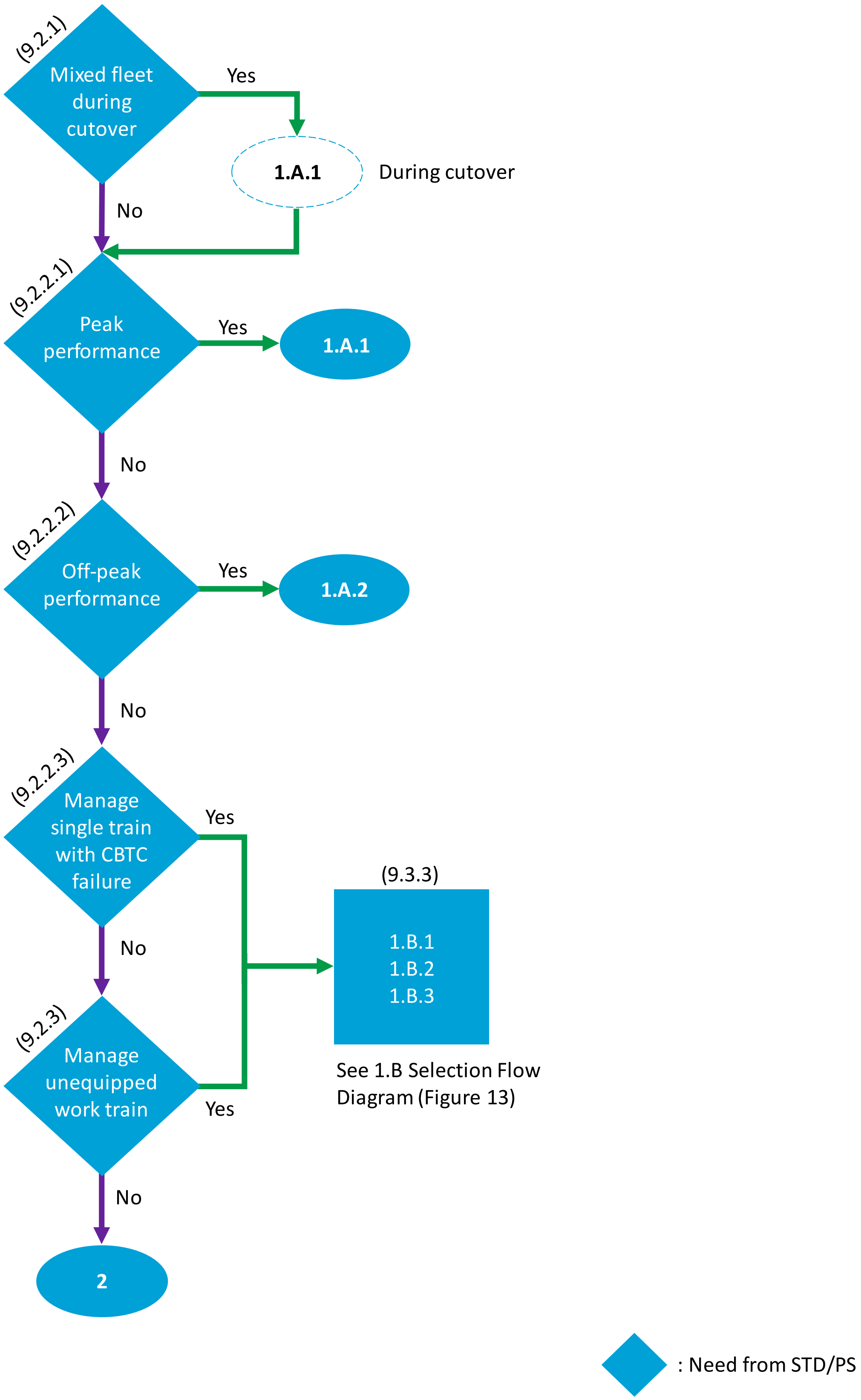


Figure 12: Alternate Decision Flow Diagram for STD/PS Selection

9.3.3 Choosing Among 1.B Categories

Table 13: Category 1.B Secondary Systems Designed to Handle a Single Non-CBTC Train

Category	Type
1.B	**Secondary System designed to handle a single non-CBTC train**
1.B.1	Capable of one train per interstation
1.B.2	Capable of one train in between two interlockings
1.B.2.1	With detection devices everywhere
1.B.2.2	With detection devices only at interlocking
1.B.3	Without territory specific headway performance, with detection devices everywhere

If the need for managing a single train with CBTC failure or non-equipped work train is established, the level of STD/PS appropriate for a particular project must still be defined. Choosing among the 1.B Categories is the equivalent of fine-tuning the level of STD/PS to implement. It is dependent on the track configuration and the capacity needed along the line which may not be the same between each pair of stations. The method for choosing between the 1.B Categories can be the following:

1. Choosing between Category 1.B.1, capable of one train per interstation, and Categories 1.B.2/1.B.3, not capable of one train per interstation

2. Evaluating the need for detection devices everywhere (1.B.2.1/1.B.3) and detection devices only at interlockings (1.B.2.2)

3. If detection devices everywhere are needed, then choosing between Category 1.B.2.1 with signals at interlocking and Category 1.B.3 without any signals

9.3.3.1 Choosing Between Category 1.B.1 One Train per Interstation and Categories 1.B.2./1.B.3

The main difference between Category 1.B.1 and Categories 1.B.2/1.B.3 is the performance of the secondary system regarding management of a single non-CBTC train. If managing one non-CBTC train per interstation is needed, then Category 1.B.1 is preferred, and if not, other categories are possible. Functionally, another important difference between Category 1.B.1 and Categories 1.B.2/1.B.3 is that projects in Category 1.B.1 are able to manage wayside controller failure more efficiently, as noted in Section 7.1.3 Wayside Failures.

Therefore, the two needs to evaluate this choice are:

- Need for station to station control of non-CBTC trains
- Need for back-up for wayside controller failure

The need for managing a non-CBTC train per interstation is dependent on the track layout and should be evaluated by the transit agency based on the configuration of its system.

The industry survey showed that projects in Category 1.B.1 are more common than projects in Categories 1.B.2/1.B.3.

9.3.3.2 Choosing Between Detection Devices Everywhere (Categories 1.B.2.1/1.B.3) and Only at Interlockings (Category 1.B.2.2)

There are two implementation methods of the secondary detection system: with secondary detection devices everywhere (Categories 1.B.2.1/1.B.3), or with secondary detection devices only at interlockings (Category 1.B.2.2).

Interlocking protection is presented in Section 5 – Secondary Train Detection/Protection Systems, and includes approach locking, route locking, detector locking, and traffic locking. This protection can technically be provided by both the CBTC system for CBTC equipped trains and by the secondary system for all trains. The industry survey showed that when STD/PS is present, the STD/PS provides interlocking protection for all trains, CBTC and non-equipped. The CBTC system is used to provide interlocking protection for CBTC trains only in Category 2, when STD/PS is not present. In this case, the wayside controller is providing the interlocking protection.

The main factor for this decision is whether there is a need to track non-CBTC trains everywhere with the STD/PS. The industry survey showed that having secondary detection devices only at interlockings (Category 1.B.2.2) is very rare in comparison to projects with secondary detection everywhere (1.B.2.1 and 1.B.3). Being able to track non-CBTC trains accurately using secondary detection devices everywhere is beneficial for providing protection around the non-CBTC trains; it is particularly important to protect non-equipped work trains. It also allows operation of CBTC trains around the non-CBTC train efficiently and more closely than in systems with detection devices only at interlockings. Furthermore, less distance is required for running in restricted speed mode by a train with CBTC failure to resume CBTC operation.

In summary, the needs to evaluate this choice are:

- Need to track non-CBTC trains accurately, to facilitate management of unequipped work trains
- Need for CBTC trains to follow non-CBTC trains closely, especially in the case of a single train with CBTC failure
- Need to avoid running for long distance to resume CBTC operation after a train experiences a recoverable CBTC failure

9.3.3.3 Choosing Between Categories with Detection Devices Everywhere With Signals at Interlockings (Category 1.B.2.1) and Without Signals (Category 1.B.3)

The difference between projects in Category 1.B.2.1 capable of one train in between two interlockings and 1.B.3 without territory specific headway performance is the presence of signals at interlockings, and in particular the presence of a method of enforcement of the signals.

Even if the agency decides to not have any interlocking signals, switch position indicators might be installed to provide the position of the switch to non-CBTC trains so the main difference between the two categories is a method of enforcement of those signals.

When the legacy system does not include a method of enforcement, it is not practical to start using one with the introduction of CBTC, due to the need to equip the trains. In this case, the project may be in Category 1.B.3 with or without switch position indicators, or in Category 1.B.2.1 with interlocking signals without a method of enforcement. Those categories are then equivalent.

When the legacy system includes a method of enforcement which is to be retained, then the project is in Category 1.B.2. The decision of whether to retain the method of enforcement is to be made by both the signaling team of the agency and the team in charge of the rolling stock.

In summary:

- If the legacy system does not include a method of enforcement of signals, then options 1.B.2.1 or 1.B.3 can be used and are equivalent. There may be either signals without enforcement or switch position indicators.
- If the legacy system includes a method of enforcement of signals and the method can be kept in the new system, option 1.B.2.1 is preferred.

9.3.3.4 Decision Flow Diagram for Choosing Between 1.B Categories

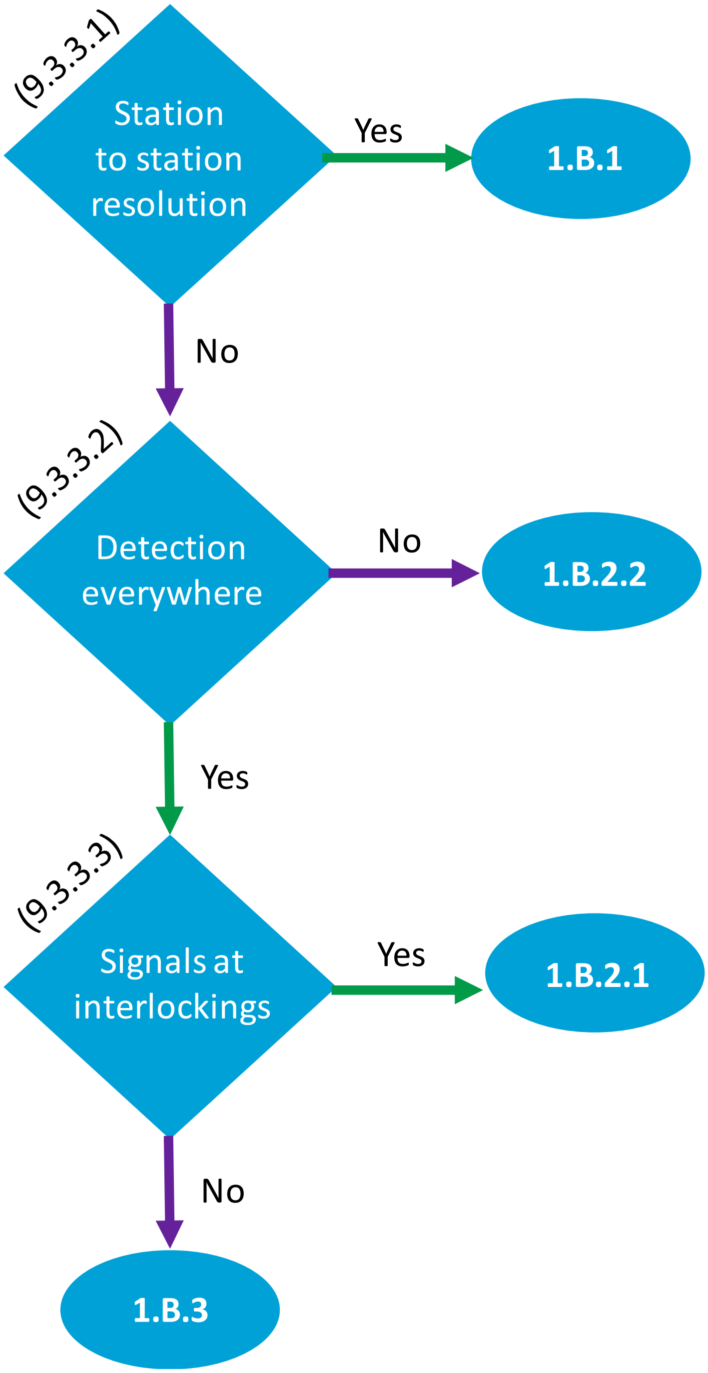


Figure 13: Decision Flow Diagram for STD/PS Selection – Choosing between 1.B Categories

9.4 Other Considerations

9.4.1 Other Potential Influences

All the factors discussed previously are usually the main factors in the assessment done by engineering and operation departments. There are several other influences which may affect the decision process. Those influences may not be identified as factors, but may be in the decision maker's mind. For instance, if there is already significant solid-state equipment in service or electronics onboard the trains, the agency may be more comfortable with CBTC technology, and may be less likely to require a high degree of back-up by a secondary system. Below are some of the most common influences.

9.4.1.1 Supplier Influence

- CBTC suppliers are adapting to client needs but are also capable of influencing transit agency selection regarding the STD/PS.
- Though most of the CBTC suppliers are also track circuit vendors, most of them have been advocating for axle counters over track circuits. One reason is that axle counters can be installed independently of the existing signaling system, which works well for upgrade projects.
- Few CBTC suppliers have products and experience without STD/PS, so suppliers tend to offer CBTC with STD/PS. Regarding mass transit projects, based on the industry survey, only two CBTC suppliers so far have deployed a system without STD/PS on greenfield projects. Some of the first CBTC projects in the 1980s were implemented without STD/PS and have been very successful, such as in Vancouver, BC, Canada (see Case Study 2 – British Columbia Rapid Transit Company SkyTrain). Despite the success of these projects, the proportion of projects without STD/PS has remained small.

9.4.1.2 Type of Legacy System – Culture Change

In cases where the legacy signaling system already includes electronics, as in a cab signal system, the transit agency culture change with transition to CBTC is less of a shock than for agencies with no electronics experience. The result is:

- The transit agency with electronics experience is already used to an advanced signaling system and may view a back-up system less favorably than a transit agency with a conventional wayside signal system.
- It is possible that the number of field devices is already minimal, having signals only at interlockings for instance, and therefore the transit agency is more likely to embrace a low level of STD/PS.

9.4.1.3 Grade of Automation

Based on the industry survey, the grade or level of automation does not appear to have a direct impact on the level of STD/PS except in the case of greenfield driverless projects. The survey revealed that, so far, all the projects without STD/PS were greenfield driverless projects. However, not all greenfield or brownfield driverless projects are without STD/PS.

Without an operator onboard, any system failure would result in a long delay, whether there is an STD/PS or not, since an operator needs to reach the stranded train from another location before it can be moved.

9.4.1.4 Grade of Line

Grade of line is defined as a measure of the complexity of the line to be equipped with CBTC. For instance, projects with several interwoven lines are more complex than a single line isolated from the rest of the network. The complexity of the rail network, and the intensity of the service to be provided on that network, is likely be a factor impacting the decision for a back-up system.

9.4.2 Other Topics Not Usually Considered as Factors

This section notes some of the possible issues which, after analysis of the industry survey, turned out to not be factors in the decision of which type of STD/PS to implement.

9.4.2.1 Underground/Above Ground Systems

Based on the industry survey, there is no influence on the assessment whether the infrastructure is in tunnels, at grade, or above ground level.

From the industry survey, respondents indicated that projects with above ground territory in harsh winter locations chose to implement track circuits because broken rails are more frequent in extreme weather conditions. On the other hand, projects have cited extreme weather conditions as a reason for not having a secondary method of detection, as devices on the roadbed fail too often and impact CBTC operation availability.

9.4.2.2 Type of Rolling Stock

Whether the rolling stock is with steel wheels or with rubber tires, the industry survey did not show any relevant effect.

SECTION 10

Choosing the Secondary Method of Detection

When the transit agency decides to implement some type of secondary detection, a selection must be made as to the type of equipment to be used. This section provides information to help transit agencies make this selection. Unlike the decision regarding the functional use of an STD/PS, choosing between track circuits and axle counters is not influenced by the required functionality of the signaling system. The decision is based on regulatory and technical factors.

Track circuits and axle counters both satisfy the goal of detecting train occupancy. The principles for each method are described in Section 5 – Secondary Train Detection/Protection Systems. This section presents the benefits and limitations of each type of method. The influence of this selection on CBTC projects is also presented.

10.1 Secondary Detection System Layout

Authorizing initial CBTC train movement and providing train separation with non-CBTC trains are two of the CBTC core functions that have a direct impact on the implementation of the secondary detection system. The number of detection devices is based on the desired performance of those functions.

10.1.1 Authorizing Initial CBTC Train Movement

In systems that feature a secondary detection method, the detection devices are used to ensure that there is no obstruction on the track around the CBTC train before authorizing CBTC train movement. The obstruction could be a non-CBTC train such as a train with CBTC failure or a work train. The wayside controller uses the location reported by the CBTC trains and the knowledge of the secondary detection device layout to confirm that no “hidden” train is present before issuing a movement authority limit to the CBTC train. This function is discussed in Section 8.5 – Minimum Non-Equipped Train Length Issue.

Having more detection equipment means that train initialization can be performed at more locations. This is particularly important for managing the recovery of a train with CBTC failure or recovery of a wayside controller failure.

On projects without STD/PS, the initialization of the train relies on operating procedures.

10.1.2 Providing Train Separation with Non-CBTC Trains

For projects with detection of non-CBTC trains, CBTC allows CBTC trains to follow non-CBTC trains using the occupancy status of each block. Since no information is received by the wayside controller regarding the non-CBTC trains, CBTC keeps a vacant buffer between non-CBTC trains and following CBTC trains.

Having more detection device equipment means that CBTC trains would be able to follow non-CBTC trains more closely. This function is also important for managing trains when a train experiences a CBTC failure.

10.2 Comparison Between Track Circuits and Axle Counters

Table 14: Track Circuits vs. Axle Counters

The asterisk (*) indicates a relative advantage.

Criteria	Track Circuits	Axle Counters	Relative Advantage To
Track requirements	Isolated rails, insulated joints, impedance bonds, wire connections	*None	Axle counters
Length of track section	Limited by feed power, ballast leakage	*Unlimited	Axle counters
Traction current return interference	Yes	*No	Axle counters
Broken rail detection	*Yes (only certain kinds)	No	Track circuits
Dependence on wheel-rail electrical interface (shunt)	Yes	*No	Axle counters
Detects vehicles entering upon track in middle of section	*Yes	No	Track circuits
Initialization and reset procedures	*No	Yes	Track circuits
Functional scope	Detection, direction (by following sequence with adjacent track circuits), average speed through entire section (by also measuring time)	*Detection, direction, car counting, train length, average speed between detectors (by also measuring time)	Axle counters (car counting and train length are determined non-vitally)
Installation	More complex	*Quicker, no modification to track. May be overlaid over existing track circuits.	Axle counters
Modification of layout	Complex, involves insulated joint and impedance bond changes, new holes in the rail	*Simple due to wheel sensors being clamped to the rail (depends on manufacturer). Third rail modification might be required to facilitate maintenance.	Axle counters
Maintenance	Periodic readjustment required due to changes in ballast resistance	*Highly reliable. Minimum maintenance.	Axle counters
Vital Operation	Yes	Yes (CENELEC/EN 5012X, SIL 4)	Equal

As shown in Table 14, the axle counter technology has a distinct overall advantage.

For the criteria where track circuits have an advantage:

- Hazards from vehicles that enter upon the track in the middle of a section can be mitigated by procedure.
- The initialization and reset procedures for axle counters are a burden during failure scenarios, and not as part of normal operation.
- For broken rail detection, track circuits which can detect some of the rail breaks are more favorable than axle counters which cannot detect any break.
- Another important advantage of track circuits which is not listed above is that transit agencies are familiar with the function and maintenance of track circuits. Alternatively, when an agency introduces CBTC technology, new equipment is being introduced and it is an opportune time to replace what is likely an aging track circuit system with a new axle counter system.

Among the advantages of axle counters over track circuits, the following are the most important in CBTC projects:

- Axle counters can be installed and operate in parallel with existing track circuits. This is a major factor for brownfield projects because it eases installation and can also ease the cut-over.
- Block length can be as long as necessary. Though there are some track circuits which can also be very long (6,000 feet or more), not all types of track circuits allow block lengths long enough such that the layout is based only on the functional needs. Some technical factors may require more track circuits than functionally necessary.
- Axle counters eliminate interaction between train detection and traction current return.
- Regarding the life cycle cost, based on discussions with suppliers and transit agencies using axle counters, track circuit procurement cost is lower than axle counter but installation and maintenance of track circuits requires more labor. Also, since axle counters have no length limitation, there may be less equipment than with track circuits, so the overall life cycle cost of an STD/PS is considered less with axle counters than with track circuits. This is based on general principles; application specifics must be considered for each project. Life cycle cost is dependent on the type of track circuits and the type of axle counters used. For this reason, life cycle cost comparison is not included in Table 14 Track Circuits vs. Axle Counters.

The comparison is made for secondary systems in CBTC projects, and not for conventional signaling systems. Though the results seem to favor axle counters, the fact that the industry in North America is very familiar with track circuits and not experienced with axle counters may play a more important role with use in conventional signaling system projects.

It is possible to equip a system with both types of secondary detection. For instance, there are projects where the mainline is equipped with axle counters, while the yard is equipped with track circuits. Although it is not clear why track circuits were used in the yard and not axle counters, the benefits of having a different method of detection based on the location should be considered. Despite having to maintain two different types of equipment, it may help agencies decide to not equip the yard with CBTC. Other examples include projects in Category 1.B.2.2, where track circuits are used to provide detector locking protection in an interlocking, and axle counters are implemented for accurate train detection needed for flank protection.

10.3 Industry Survey

Based on feedback from more than 70 CBTC projects around the world, the industry survey revealed that among the projects which implemented STD/PS:

- 39% of projects use track circuits
- 61% of projects use axle counters

The few projects using both axle counters and track circuits were not considered to derive these numbers. Secondary methods of detection have shifted from track circuits to axle counters in recent decades. All CBTC suppliers can now provide both options and have project experience using track circuits and axle counters.

The percentage shifted over time:

Before 2005, among projects with STD/PS:

- 91% of projects use track circuits
- 9% of projects use axle counters

After 2005, among projects with STD/PS:

- 29% of projects use track circuits
- 71% of projects use axle counters

Because CBTC has become the most popular technology for mass transit, the number of projects since 2005 has increased significantly. The percentages among all surveyed projects (39% with track circuits, 61% with axle counters) are closer to the percentages of projects after 2005 (29% with track circuits, 71% with axle counters) than the percentages of projects before 2005 (91% with track circuits, 9% with axle counters).

Note that most recent projects which use track circuits as a secondary method of detection are brownfield projects.

Out of more than 70 projects which were surveyed, only three were without STD/PS, representing about 4%. Including all mass transit and airport links, an estimate of CBTC projects without STD/PS is between 5% and 10% around the world. As noted previously, brownfield projects require STD/PS more often than greenfield projects, so in parts of the world where brownfield projects are more frequent, like Europe and North America, the percentage of projects with STD/PS is higher. With the popularity of driverless systems which are more inclined to not use any STD/PS, the ratio is likely to change in the future.

From the industry survey, Table 15 describes the relation between the category of a CBTC project and the choice of secondary detection system.

Table 15: Type of Secondary Detection Equipment in Different Categories of CBTC Projects

Type	Category	Type	Comment from the industry survey on the detection method
Systems with STD/PS	**1.A**	**Secondary System capable of revenue service**	
	1.A.1	Secondary System capable of peak revenue service	Track circuits only
	1.A.2	Secondary System capable of off-peak revenue service	Track circuits only
	1.B	**Secondary System designed to handle a single non-CBTC train**	
	1.B.1	Capable of one train per interstation	Majority with axle counters and a few with track circuits
	1.B.2	Capable of one train in between two interlockings	Majority with axle counters and a few legacy projects with track circuits
	1.B.2.1	With detection devices everywhere	Majority with axle counters and a few projects with track circuits
	1.B.2.2	With detection devices only at interlockings	Usually with track circuits or with both track circuits and axle counters
	1.B.3	Without territory specific headway performance, with detection devices everywhere	With axle counters and with track circuits
Systems without STD/PS	**2**	**No Secondary System**	

SECTION 11

Conclusion

Many mass transit agencies are now using or considering CBTC technology to equip their new lines or to upgrade their existing systems. Among the numerous benefits of CBTC, the main attractive feature for agencies is the possibility to increase their system capacity by reducing the headway between trains. This capacity increase is accompanied by other benefits such as continuous speed control, more flexible operation, and less equipment installed on the roadbed and thus less wayside maintenance. Although conventional signaling systems could technically provide similar headway to CBTC, they would require more wayside equipment to be deployed which results in more installation work and wayside maintenance needed. Minimizing wayside equipment is hence an additional factor in the decision to implement CBTC technology.

This guide has been developed for transit agencies which have already decided or are considering CBTC technology. Attention should be given to the need for a possible secondary system because a system that includes both CBTC and a secondary system may result in an overly complicated system harder to deploy and to maintain than anticipated.

The guide describes the different levels of secondary systems used in CBTC projects. Some projects have successful operation without any secondary system at all. Some have secondary systems capable of managing a single non-CBTC train (train with CBTC failure or non-equipped work train) while other projects are capable of some level of revenue service. Choosing more capabilities from the secondary system results in more adverse effects on the deployment effort and maintenance, and on the availability of the CBTC system.

On the other hand, having no STD/PS requires the transit agency to rely on operating procedures alone during system failures and further restricts the operation of unequipped work trains.

- The work train issue may be included as a factor for secondary system selection, or the secondary system selection may be a factor on whether to equip the work trains. There are examples of projects without a secondary system where non-equipped work trains have been managed successfully. Equipping work trains is recommended when there is no secondary system and revenue service operation is 24/7; this avoids frequent operation of CBTC and non-CBTC trains at the same time.

In summary, the proposed decision process is as follows.

- Acknowledge that there are several successful CBTC projects without STD/PS and recognize that the ideal solution to minimize deployment and maintenance is the lowest level of STD/PS.
- Evaluate the need for mixed-fleet operation with CBTC trains and non-CBTC trains. If mixed-fleet is needed, an STD/PS capable of revenue service is needed, at least temporarily. Transit modernization programs, often combining rolling stock and signaling system replacement, should be managed to avoid the need for mixed-fleet operation.
- Decide whether the STD/PS should have the capabilities to run peak revenue service. The guide showed that this need is present only in a very particular case where non-CBTC trains from other lines are using the CBTC territory.
- Evaluate the need for the STD/PS to provide a back-up for revenue service, i.e. to be capable of off-peak revenue service. Trade-off analysis between the frequency of use and the effort of deployment and maintenance should be performed. The industry survey showed that in most cases, the effort of deployment and maintenance is too large to justify a full back-up system.

- When it is decided that no back-up for revenue service is needed, assess the need for managing a single train with CBTC failure and/or non-equipped work train. The industry survey showed that there is a recent trend to be able to manage a *single* train and/or non-equipped work train with STD/PS.
- There are different methods of implementation based on the performance of the STD/PS to manage non-CBTC trains. The STD/PS can manage, with limited operating procedure, one train per interstation, or one train between interlockings; or it can simply track the non-CBTC trains for other trains to continue running in CBTC mode around the train with CBTC failure.

For agencies selecting a secondary system, track circuits or axle counters may be used as the method of train detection. Although track circuits have been more commonly used in the past and agencies are very familiar with them, recent trends in CBTC projects around the world show that axle counters are becoming the norm in CBTC projects. One of the major reasons is that most new CBTC projects are signaling upgrades where axle counters may be installed independently from the existing track circuits and traction current return system. Another reason is that the length of a section defined by axle counters is not limited, which matches well with certain CBTC requirements, whereas track circuits have a limited length. However, axle counters, unlike track circuits, do not provide any level of broken rail detection. This is an issue which needs to be addressed by agencies who have relied upon and benefitted from the track circuit's ability to detect a complete non-conducting fracture of the running rail.

The goal of this guide is to provide all information which should be considered in evaluating the need for an STD/PS. In addition to the information about existing systems, failure management, and whether to equip work trains, the guide proposes a list of major considerations to be assessed by the transit agency to define if a secondary system is needed and, if needed, which level of secondary system is the minimum necessary. While performing this assessment, agencies should keep in mind that the minimum level of STD/PS is the desired one, to avoid its adverse effects on complexity, maintenance, and availability, and that any added functionality comes with additional consequences on the deployment and future operation of the system.

SECTION 12

Case Studies

12.1 Port Authority of New York & New Jersey, AirTrain JFK Case Study

12.1.1 AirTrain JFK

The AirTrain, operating at John F. Kennedy International Airport (JFK), in New York City, is an 8.1-mile (13 km) driverless fully automated light rail system that provides intra-airport transportation as well as connection between JFK Airport and New York City's mass transit system with stations in Jamaica and Howard Beach, Queens, New York. The system operates a 24/7 service over three lines using 32 Bombardier Innovia light rail cars operating in one to four-car trains, and carries about 22 million passengers per year. The project was developed by the Port Authority of New York and New Jersey (PANYNJ), the operator of JFK Airport, and is currently operated by Bombardier Transportation under a maintenance and operations contract.

12.1.2 Background of the Project

Construction of the AirTrain JFK commenced in 1998 following the award of a Design-Build-Operate-Maintain (DBOM) contract to a consortium of four firms operating as the AirRail Transit Consortium. The system opened for service in December 2003.

Bombardier Transportation built and supplied the rolling stock—32 Innovia MK-II single cars—whereas the signaling system was supplied by Alcatel Canada, now known as Thales Rail Signaling Solutions (TRSS). The rolling stock and signaling system technologies were modelled after the SkyTrain in Vancouver, BC, Canada and the Kelana Jaya Line in Kuala Lumpur, Malaysia. The use of CBTC technology was the preferred and only choice, including a decision not to use any secondary train detection system.

- Award date: May 1998
- Type of project: New line
- Revenue service date: December 2003
- Secondary detection system: None
- Signaling system supplier: Thales Rail Signaling Solutions

12.1.3 Legacy System

AirTrain JFK was a new line that did not replace another rail transportation system.

12.1.4 CBTC System

Thales' signaling technology used for this project was an evolved version of its first generation of CBTC systems, which has been around since the 1980s, originally developed for the Vancouver SkyTrain. Designed for moving block and full ATO operation, the system relies on continuous track-mounted inductive loops for communication between carborne and wayside CBTC equipment. Wire cables forming a loop are mounted along the running rails with a transition every 82 feet (25 meters) where carborne equipment detects a phase change. The distance traveled between the phase changes is calculated by a carborne odometry system. Accumulated positioning error is reset at each phase change. The data transmission between loop and carborne CBTC is inductively coupled at 36 kHz and 56 kHz. Unlike the CBTC communication over the radio that has been deployed on many recent CBTC projects, the closed architecture of inductive loops makes any unauthorized access and intrusion to its communications components very difficult; however, their installation and maintenance can be very challenging. In general, inductive loops have limited data communications capacity, and any information other than signaling data cannot be easily added, unlike more recent CBTC projects.

At the core of the carborne equipment is the Vehicle Onboard Controller (VOBC). Each car is equipped with one VOBC and antennas which serve as a communications interface to wayside loops. Each VOBC has a dual Control Processing Unit (CPU) that requires both units to agree before commands to the train can be issued. With coupled cars forming a train consist, local VOBCs act independently, but only one assumes control of the train, while others remain in standby mode. Should the active VOBC fail, the system will switch to a standby VOBC which will automatically take control of the train. Other than connections to train lines, there is no communication between train VOBCs.

The Vehicle Control Center (VCC) is the wayside portion of the ATC system responsible for handling train movements (via VOBCs) and ensuring safe spacing between the trains. The VCC also controls the movement of switches, and enforces track closures and speed restrictions which may be set by the Control Operators. There are two VCCs, one for the mainline and one for the yard, located at the control center. The VCC communicates with each VOBC at least once per second. Each VCC has three Processing Units (PUs), operating in parallel. Those PUs are monitored by a comparator which ensures that at least two PUs agree on all pertinent safety aspects before the execution of any command.

With only one VCC handling the mainline, failures could lead to system-wide halts and stoppage of revenue service. In cases of communications loss or a need to recover/reboot the VCC, for example, all trains on the mainline require manual reentry into ATO. This is achieved by driving each train through a designated mainline entry point. One of the recently deployed enhancements to VCC was an addition of an auto-restart feature, a function which allows system-wide pick up of all trains back to ATO following the system reset, eliminating the need for manual recovery. This works only if no train has been moved (or subjected to other manual intervention) prior to the reboot. As VCC equipment turned out to be very reliable, this function has not been used in years.

The systems also features a System Management Center (SMC), which provides a higher level of train management including oversight of VCCs. The SMC also allows the operator to interact with system-level service operation management.

The Station Controller System (SCS) is in communication with the VCC, and can command and control switches, platform screen doors, and platform emergency stop buttons, as well as drive switch position indicators.

12.1.5 Secondary Train Detection and Protection Systems

AirTrain JFK has no secondary detection or protection system. The only wayside indications are switch position indicators to specify to the driver the switch position when a train is driven manually.

12.1.6 Feedback on the Deployment

The project was a greenfield project. All trains started revenue service on the entire system at the same time.

12.1.7 Feedback on Operation

As there is no secondary detection and protection system, the CBTC related failures are handled using operational procedures and CBTC management features.

In cases where a failed VOBC cannot be successfully recovered, the affected train must be operated manually and removed from CBTC territory. To facilitate such recoveries and manual driving, the Control Operator assigns and reserves the route which in turn protects the “manual train” by inhibiting any other automatic trains from entering the reserved route. The speed of manual trains is limited to 15 mph. Given that there are no wayside signals, the driver relies on switch position indicators to confirm switch position.

However, when a failed VOBC can be successfully recovered, the affected train must be manually reentered into ATC by manual driving over “entry points” (loop boundaries).

During the early stages of CBTC deployment, AirTrain JFK had experienced a few onboard controller failures which made the train unable to operate in CBTC mode, but over the years many issues and software bugs have been ironed out, which in the end led to improved overall performance and only a few onboard controller failures per year.

VCC functional failures, however, result in a system-wide halt, and trains cannot be moved until the VCC is recovered. If none of the trains were moved (manually recovered) prior to completing the reboot of the VCC, all affected trains are restored to automatic mode. However, if any train was moved manually, each train must be reentered into ATO.

12.1.8 Feedback on Maintenance

Most wayside maintenance work is performed during the nighttime non-peak hours while single-tracking. The system was designed to include service patterns for trains based on the area in the track that needs repair. Given the VCC architecture, using two out of three voting logic, VCC maintenance, upgrades, and replacement of equipment could be done with minor or no impact to revenue service.

Equipping different maintenance vehicles with CBTC equipment requires the development of specific onboard controllers for each car, which calls for significant development, maintenance, and operating costs. As an alternative, AirTrain JFK designed and built VOBC equipped trailers which can be coupled to different work cars, as needed, and pulled along. The eight-foot trailer, called a Vehicle Onboard Monitor (VOBM), features its own Uninterruptable Power Supply (UPS) and full VOBC equipment. The system reports localization of the work car which allows protection around it from other trains, confirms that work cars are within the work zone limits, and can block switches when a work car is in the interlocking area, if not already done by the route reservation. The system cannot, however, command or stop the train, as the work car movement remains under the full control of the driver. Movement of a work car is performed at low speeds.

12.1.9 Feedback on the Broken Rail Issue

Over its 13 years of operation, AirTrain JFK has not experienced any broken rail events. There are several factors that have contributed to this clean record even though the guideway is elevated and exposed to weather elements throughout the year. The inspection program consists of visual inspections of the rail performed several times a month and during any other regular track maintenance activity. Also, the weight of the running rail is the same as used for heavy-rail subway cars, but the stresses are much lower due to the use of light rail cars. Holes in the rails have been noted, but are attributed to negative return. However, the holes are not as numerous as found on systems using track circuits.

As part of the daily preparation for service, a revenue train is used to sweep the guideway and ensure that the system is clear for service. The “sweep train” runs in ATO at a reduced speed and is occupied by personnel standing at the front of the train looking outside for anything abnormal, including rail problems.

AirTrain JFK uses a specially designed test vehicle to perform ultrasonic and track geometry inspections on an annual basis.

12.1.10 Future Projects

AirTrain JFK does not have any plans to add any secondary train detection and protection system. In terms of general system performance, AirTrain JFK has incorporated numerous enhancements to its originally deployed CBTC to improve revenue service and optimize the maintenance efforts.

12.1.11 Conclusion

Key takeaways from this greenfield driverless airport link case study are summarized below.

1. No secondary detection and protection system.
2. There are CBTC system functions to handle train failures.
3. No broken rail incidents since the introduction of passenger service, largely because of specific system characteristics and due to an effective preventative inspection program. This may suggest that protection against broken rails may be inherent to a system design and complemented with an appropriate inspection program.
4. Reliable wayside controller (VCC) drives the system availability figure. A new feature has been added to the CBTC system which allows a restart of all trains back to ATO mode immediately after VCC reboot/recovery.
5. Recovery of trains with CBTC failure is handled through operating procedures and with the use of some CBTC features. However, handling of halted trains using those two processes is not as efficient as the use of a secondary system.
6. Despite the regular maintenance efforts, onboard CBTC equipment failures are inevitable, although the count is low. This is expected, since there is more onboard CBTC equipment than anywhere else, and because onboard CBTC equipment is subject to a harsher environment.
7. AirTrain JFK has three CBTC equipped trailers which can be attached to a maintenance vehicle before running on the line.

In summary, AirTrain JFK has been operating safely and efficiently from its opening date without any type of secondary train detection and protection system. Operating procedures and CBTC features are in place and used when there is a train failure.

12.2 British Columbia Rapid Transit Company Case Study, SkyTrain

12.2.1 British Columbia Rapid Transit Company

The British Columbia Rapid Transit Company, Ltd. (BCRTC) is a subsidiary of TransLink, the South Coast British Columbia Transportation Authority which oversees most of the Metro Vancouver region’s transportation infrastructure and networks. On behalf of TransLink, the BCRTC maintains and operates the West Coast Express commuter service and the SkyTrain light rail rapid transit system.

Launched in 1986, SkyTrain was originally conceived as a legacy project of Expo 86 to showcase the fair’s theme of “Transportation and Communication”. The SkyTrain technology, originally known as Advanced Light Rail Transit (ALRT), was developed in the 1980s by the Urban Transportation Development Corporation (UTDC) of Ontario, Canada, now a division of Bombardier Transportation, Inc. The system incorporated driverless moving block automatic train control originally developed for the U-Bahn’s Line 4 in West Berlin, Germany (supplied by SEL Canada Ltd., and now a division of French-based Thales Group) and 114 of UTDC’s light rail cars.

With successive expansions in 1990, 1994, 2002, and 2016, the agency nearly tripled its original network size to what is now a system of 39 stations and 44 miles (70 km) of revenue track linking downtown Vancouver to the region’s northeast and south municipalities, using dedicated right-of-way made up of bridges, tunnels, at grade, and mainly elevated corridors.

Today, SkyTrain provides service to 250,000 daily riders on the Expo, Millennium, and Evergreen Lines using a fleet of three different car generations totaling 340 CBTC equipped vehicles. These trains can operate in configurations of two-, four-, or six-car trains, are capable of automatic coupling/uncoupling (among same car class), and can travel at up to 55 mph (90 km/h). Full ATC operation allows reduced headways as low as 75 seconds.

The original Expo Line was deployed as a CBTC greenfield project, whereas subsequent line expansions were integrated into an existing network via a cut-over approach after rigorous testing and extensive revenue service simulation using existing fleets. Similarly, all newly delivered cars were fitted with carborne CBTC equipment and tested at the carbuilder’s facilities, an approach which allowed quick integration of new fleets into passenger service shortly after delivery.

12.2.2 Background of the CBTC Project

Starting in late 1960s through the mid-1970s, local authorities carried out several studies assessing different transportation systems to address the region’s growth and future transit needs. Some of the early planning efforts looked at the conventional subways but reports concluded that there was not enough patronage to support the large capital investment. As buses were already the backbone of the region’s transit system, assessment reports recommended major restructuring and expansion of the bus system into the rapidly growing suburbs. Local authorities were conscious about the region’s rapid growth, and one of its primary objectives was to create a regional rapid transit system which would link the City of Vancouver and larger regional town centers. Plans for a full-scale light rail rapid transit (LRT) system were well underway, when in the late 1970s it was announced that Vancouver would host Expo 86, a World’s Fair with a transportation theme. Expo 86 needed some sort of transportation system to link its two sites on the opposite sides of downtown Vancouver. Following the evaluation of different technologies, the most promising candidate was UTDC’s Intermediate Capacity Transit System (ICTS), then under development, but which ultimately entered service first, in 1985, as an alternative to an earlier proposed light rail link in Scarborough, Ontario.

The ICTS was specifically designed to fill the gap between subway (high capacity, but expensive) and street running LRT (lower cost, but also lower capacity) systems. A fundamental component of ICTS was, therefore, the use of a separated guideway, which, to work in an urban environment, meant building a lightweight, elevated guideway structure, short stations, and use of cars capable of running over sharp curves and steep grades. The ICTS employed light rail cars equipped with Linear Induction Motors (LIM) and steerable-axle trucks capable of such operation. These cars were initially called ALRTs and were a predecessor to the current Bombardier Innovia Automatic Rapid Transit car series.

To achieve capacity objectives with this infrastructure, it required a signaling system which would support very short headways; this could only be achieved with moving block control and full automation. The selection process involved appraisals of existing computer controlled systems, most of which relied on operators to drive trains. The opinion and preference of the local population was also taken into consideration, favoring technologies which offered automation, safe and reliable systems, and not necessarily manually operated trains. In the end, the choice was made to go with a driverless system and requirements calling for an architecture that could also allow future expansions.

Overall, the ICTS provided a short-term solution for Expo 86 and a long-term solution to downtown and regional transit needs. From that point, it was a simple step to expand the Expo 86 shuttle to a full-fledged rapid transit line.

The contract between provincial and local government representatives and UTDC was signed in 1981 to build Phase I. After two years of planning and engineering, the construction of the system started in 1983 and finished by early 1986, six months ahead of the Expo 86 timetable.

The Expo Line was commissioned and approved for revenue service in late 1986, making it the third driverless greenfield CBTC rapid transit system after Scarborough, ON, and Detroit, MI in North America.

- Award date: December 1981
- First revenue service date: 1986
- ATO operation, driverless
- CBTC coverage in the yard
- CBTC inductive coupling provides communications between wayside and carborne
- Secondary system: none

Phase II, featuring an expansion of 1.9 miles (3.1 km), was completed in early 1990, followed with Phase III's addition of 2.7 miles (4.3 km) by spring of 1994. As part of Phase II, several enhancements were made to the system based on lessons learned and operational experience gained over the years. The most significant was the implementation of the second generation of ATC which featured newer technologies and allowed for greater flexibility in train control.

In the summer of 2002, under the Millennium Line Phase IV and V expansion, an additional 12 miles (20 km) and 13 new stations were integrated into the system, together with 60 new generation MK-II cars. This addition required a complete redesign of and upgrades to the existing Operations and Control Center (OCC), including the enhancements to ATC software to handle the addition of the new MK-II cars.

As part of these efforts, a very detailed cut-over plan was designed to minimize the impact on existing revenue service, as it was essential to maintain normal service levels throughout the construction and cut-over phases. To facilitate installation of new equipment to OCC, the control of the entire SkyTrain system and operations were temporarily moved to a Control Operator's Training Room for a period of two months. It served as an interim control room until the completion of renovations. The transition proceeded without a glitch or interruptions to passenger service. The cut-over plan also included retraining Control Operators on the new system enhancements and operating procedures.

12.2.3 Legacy System

SkyTrain did not replace any legacy rapid transit system, though parts of its alignment were duplicated over the BC Electric Railway's decommissioned corridor, abandoned in the 1950s.

12.2.4 CBTC System

All train movements are controlled and managed from the Operations and Maintenance (OMC) center. The SkyTrain system relies on Seltrac CBTC initially supplied by Alcatel Canada. The basis of this train control system was originally developed in Germany for control of both rapid transit and conventional rail systems, however much of the enhancements for the rapid transit application were done by Alcatel, with a significant engineering component designed specifically for SkyTrain. Lessons learned on the Vancouver application have been instrumental on subsequent SkyTrain-like ATC systems and CBTC projects in Ankara, Turkey; Kuala Lumpur, Malaysia; AirTrain JFK, New York; Las Vegas, Nevada; Beijing, China; and Yongin, South Korea.

The Seltrac CBTC relies on constant data communications between trains and wayside computers to exchange essential train data such as speed, gradient, and station locations. This information is rechecked and verified by vital software algorithms to ensure safety and reliability. The communications link between wayside and carborne controllers is accomplished through high capacity inductive loop data cables laid through the entire length of the guideway in sections averaging 1.2 miles (2 km) in length. At intervals of approximately 82 feet (25 m), the inductive loop cable is transposed to cause a phase shift in the signal at each loop crossover. Using onboard antennas, the carborne equipment detects the crossovers and counts them. The information, when combined with odometry signals generated by axle-mounted tachometers, provides a safe, highly accurate train position measurement.

The system uses a moving block train separation principle to keep trains at a safe distance. Portions of track reserved for a single train are adjusted in very small units and are updated as frequently as once per second. Unlike a conventional fixed-block system, the minimum spacing is speed dependent, with fast moving trains given more stopping room than slow moving trains. This allows maximum capacity while ensuring safety throughout the system. The wayside control is in continuous communication with all trains in all territories. The Vehicle Control Center (VCC) receives position information from each train and calculates the allowed speed and safe stopping points between consecutive trains. Moving trains are therefore constrained to stay within their envelope defined by the speed, braking rate, and available space, so that they do not exceed their respective safe stopping points. Depending on the severity of communications loss between the wayside and carborne controllers, the ATC enforces appropriate fail-safe states, i.e. command emergency braking to non-communicating trains, temporary speed reduction to indirectly affected but otherwise communicating trains, or halt all trains until the issue is resolved.

12.2.5 Secondary Train Detection and Protection Systems

SkyTrain’s network does not have a secondary detection or protection system nor any conventional signals on the wayside.

12.2.6 Feedback on the Deployment

The original SkyTrain Expo Line and ensuing expansions are greenfield CBTC projects which had both wayside and carborne CBTC deployed at the same time. One of SkyTrain's keys to success was that its construction schedule was carefully planned from the start by transit professionals, not by contractors or vendors. This management allowed ensuing work to proceed with minimum delays. When an unforeseen issue developed during the deployment, the alternatives were carefully evaluated and implemented.

In late 2016, SkyTrain added 28 new third generation four-car trains to alleviate capacity needs on the Expo and Millennium Lines. The cars were delivered in time for the opening of the Evergreen extension to the Millennium Line, featuring 6.8 miles (11 km) of new track and 7 stations.

12.2.7 Feedback on Operation

As part of the onboard redundancy scheme, older fleets feature a computer controller, known as a Vehicle Onboard Control (VOBC), in each car; whereas recently delivered MK-III four-car trains only have two VOBCs. In a multi-car train consist, any of the VOBCs can control the train (in the form a master-slave arrangement). The master VOBC is typically assigned automatically by the system upon the train’s entry to ATO mode, but if needed the Control Operator can manually command a switchover to any other available VOBCs on that train. The master VOBC will continuously monitor and report train position, its speed, and general conditions to the VCC; in response to VCC commands, the master VOBC controls train movement by commanding acceleration, braking, direction of travel, door control, and emergency braking. When the active VOBC detects a loss of communication with VCC for more than 3.3 seconds, or longer than 56 feet (17 m), it will “halt” and respond in a fail-safe manner by applying emergency brakes. However, if there is an operational VOBC on any other car of the same train, before the emergency brake takes place, the system will hand over control to a standby VOBC, thereby allowing the system to resume normal operation. If emergency brakes are applied due to a halt, then manual intervention is required to reset the system, and/or drive the faulted train manually at low speed, until the automatic train control can be reestablished.

Over the years, it was found that one of the most severe disruptions to CBTC communications were those related to intermittent ground faults (arcing) on traction motors. Though infrequent, such events can generate powerful local electromagnetic interference (EMI) which in turn can disturb communications not just locally, but on other trains within range. In cases where failed or halted VOCBs cannot be successfully restored or recovered, the affected train must be operated manually and removed from the CBTC territory. Manual driving of non-communicating trains is governed and enforced by recovery procedures, managed and executed by the control center and field staff.

The Vehicle Control Center (VCC) is the wayside portion of the ATC system responsible for handling train movements (via VOBCs) and ensuring safe spacing between the trains. The VCC also controls the movement of switches and enforces track closures and speed restrictions which may be set by the Control Operators. There are six VCCs: four covering the Expo, Millennium, and Evergreen Lines, and two for the yard. The VCC normally communicates with each train at least once every second, with each VCC capable of controlling up to 125 trains in a variety of 2-, 4-, or 6-car consists. During peak service, 55 trains run on an average of 108 seconds apart on the Expo Line and 324 seconds on the Millennium Line. During off-peak hours, trains run between three to eight minutes apart depending on the line. All six VCCs are located at the OMC. Each VCC has three Central Processing Units (CPUs) operating in parallel and monitored by a comparator which ensures that at least two CPUs agree on all safety related actions before executing any commands. In the event of a discrepancy that cannot be reconciled by an elaborate set of redundancy, plausibility, and consistency checks, the conflicting CPU is automatically shut down until it can be reinitialized or repaired. If the VCC fails completely, all trains in its territory will timeout due to loss of communications and stop moving. Though this is an extremely low probability event, all trains within this VCC territory must be manually driven and reentered one by one back into the ATO which could take some time before the system is restored to normal. In recent years, the VCC's hardware and software has been updated and enhanced to incorporate line expansions and introduce more powerful CPUs. One of the scheduled enhancements to VCC will include an auto-restart component to pick up all trains automatically following the system reset, eliminating the need for manual reentry of trains described above.

The System Management Center (SMC) provides a higher level of train management and regulation, and spans all the VCCs. This includes the operation of scheduled service, incorporating automatic train launching and reduction in train service, speed regulation, and station dwell times in accordance with planned operating schedules. The SMC also drives graphic interfaces which show track, mainline status, and locations of trains. Using SMC, Control Operators can run extra trains to manage failures or emergencies, as well as command train maneuvers within the yard. The train arrivals and departures are logged to allow subsequent verification of service delivery and analysis of problems affecting service. Over time, SMC hardware and software have been enhanced to incorporate line expansions and introduce more powerful operating systems. One of the upcoming enhancements to SMC will allow separation of vital systems, so that if one system fails, the problem can be contained so that it does not impede other systems.

As the industry is moving toward radio-based CBTC, Thales Solutions proposed to SkyTrain to overlay inductive loop technology with a back-up system using radio and Zone Controllers. The two systems would work in parallel and independently, with trains picking and communicating with either one. In case of failures, for example, the system should default to the one that is healthy and available, thereby allowing uninterrupted revenue operation.

12.2.8 Feedback on Maintenance Fleet

The SkyTrain utilizes standard types of railroad work cars consisting of different sizes and lengths of work trailers. None of these cars is equipped with CBTC and their movement on the mainline is exclusively handled by operating procedures. SkyTrain service shuts down late at night, and maintenance crews have a four-hour window to access the tracks to perform necessary inspections and repairs. The manually driven work cars get access to the mainline after the last revenue train has left service.

Though strictly presented as an abstract, SkyTrain has evaluated an idea of using a frequency jammer fitted to a work car which could be used near the work zone boundaries to jam CBTC communications and inhibit the operations of CBTC trains within the work zone, in case work trains need to go on the mainline during regular service.

SkyTrain does not intend to incorporate any form of CBTC to work trains, even a degraded CBTC version for tracking purposes.

12.2.9 Feedback Regarding the Broken Rail Issue

SkyTrain uses a local inspection company experienced in general Non-Destructive Testing (NDT) methods to inspect its running rails. The contractor utilizes a custom built, slow moving push cart to perform ultrasonic inspection of running rail at regularly scheduled intervals every 24 months. In case of unclear or incomplete readings, technicians will recheck questionable areas using the hand scanners.

Over the last 30 years of operations, SkyTrain has had an extremely low count of running rail problems. One of the reasons is that system uses light axle loads on 115-pound rail. Historically, there was one incident of broken rail and three cases of serious cracks. The sole broken rail incident occurred early in the fourth year of the system’s operation during a harsh winter; the fracture took place next to a thermite weld. Ensuing investigation attributed the incident to rail being laid too hot and forces pulling the rail apart (shown by the completely vertical brittle-looking fracture). The three serious cracks identified during the regular inspections were associated with the weld repairs to rail head spalls.

As part of the daily preparations for service, the very first train of the day that enters the mainline is used to “sweep the system” and ensure that the guideway is clear for service. The sweep train runs in ATO at a restricted speed and is occupied by SkyTrain Field Operation personnel standing at the lead end of train looking outside for anything unusual, e.g. debris and general condition of the running rail. In case of spotted abnormalities, the personnel would then activate the emergency stop button and cause the sweep train to stop.

12.2.10 Conclusion:

Key takeaways from this greenfield driverless case study are the following:

1. High redundancy of CBTC carborne equipment allows SkyTrain trains to operate with minimum interruption in cases of local carborne failures.
2. A driverless CBTC architecture without STD/PS, featuring a multiple carborne redundancy scheme, ensures high system availability on one side, but adds to the project’s overall life cycle cost.
3. SkyTrain is in the process of integrating new functions to VCC software to mitigate train recovery after VCC failures (similar to the one at JFK AirTrain).
4. Work cars are not equipped with any kind of CBTC and this seems to work fine as work cars do not enter mainline before the shutdown of revenue service.
5. Inspection of running rail is carried out through regularly scheduled inspection intervals using industry recommended test procedures and tools. Conducting daily sweeps of the mainline help with detection of track abnormalities.
6. SkyTrain does not feature any conventional wayside signals; therefore, recovery of trains with CBTC failure or system-wide failures are strictly handled using the operating procedures.

SkyTrain is generally satisfied with its CBTC signaling technology and underlying architecture. Over the years, SkyTrain incorporated several changes and enhancements to the original Seltrac system which made it more reliable and flexible. Additional specific changes are being planned to make the system more robust and service SkyTrain's specific operating needs. An STD/PS was not part of the original technical specification nor ever considered subsequently. Given the system's high redundancy scheme and maintenance access to track during nightly off hours, it can be asserted that STD/PS would not bring much value for the investment, if any.

12.3 New York City Transit Case Study, Canarsie and Flushing Lines

12.3.1 New York City Transit

The New York City Transit (NYCT) Subway is a heavy-rail rapid transit system, connecting four New York City boroughs –Manhattan, Brooklyn, Queens, and the Bronx. NYCT Subway is a subsidiary of the state-run Metropolitan Transportation Authority (MTA) of New York.

NYCT Subway is the largest and busiest rail transit system in North America. The agency operates a 24/7 service on 25 lines and 469 stations with an average daily ridership of 5.7 million passengers. The system consists of tunnels under the East River, subway, and elevated corridors covering over 660 miles of revenue track. It relies on Automatic Block Signaling, using approximately 10,675 fixed wayside signals (and automatic train stops), to safely control operation of more than 6,400 revenue and non-revenue rail vehicles.

As part of the agency's extensive modernization initiative to include new technologies in its system, in 1997 NYCT Subway approved a CBTC pilot test on the 11-mile self-contained Canarsie Line (L). The project was awarded to Matra Transport International, now Siemens Mobility–Rail Automation (Châtillon, France). The installation and testing of CBTC began in early 2000 and was commissioned for revenue service by the end of 2006. Currently, the L-service on the Canarsie Line operates 25 trains an hour, an achievement that would not be possible without CBTC technology.

Subsequently, in late 2009, NYCT Subway awarded a contract to Thales Transportation Solutions (Toronto, ON, Canada) to install CBTC on the Flushing Line (7) service, which like the L line is also a self-contained subway line with no revenue connections to other lines. The installation of the CBTC system is ongoing and started revenue service in February 2017. Recently delivered R-188 cars were delivered as a CBTC-ready fleet to accommodate requirements for the upcoming CBTC migration project.

12.3.2 Background of the CBTC Projects

NYCT Subway's decision to adopt CBTC technology was made after an extensive technologies assessment study which found CBTC to be one of the most suitable solutions for the agency's short and long-term needs, offering shorter headways, greater operational flexibility, enhanced safety, lower life cycle costs, and minimal operational disruptions during implementation. The study also included recommendations on implementation strategies and proposed that the new signaling technology be proven through a pilot project on the Canarsie Line, one of the only two lines in the NYCT Subway system that is self-contained, with right-of-way not shared with other lines. Shared routes add complexity to functional requirements, and this 11-mile long two-track line, connecting 8th Avenue in Manhattan to the Rockaway Parkway station in Canarsie, Brooklyn, with its 24 stations and 7 interlockings, provided an excellent representation of the NYCT system as a whole, with elevated and subway corridors and tunnels under the East River.

Though defined as a pilot, the Canarsie Line CBTC project had multiple objectives, including re-signaling of the line, developing new acquisition processes to better manage high tech projects, and developing the CBTC interoperability requirements for all future CBTC projects. As part of the implementation strategy, NYCT shortlisted well-established signaling suppliers, and asked for a demonstration of their respective CBTC technologies on a designated test track. The results of these trial tests were later used to determine technical and project management proposals, and to conduct system safety audits, as part of the efforts to select the most appropriate CBTC technology for NYCT.

In December 1999, the CBTC signaling contract was awarded to several contractors, who formed a "CBTC Joint Venture" to design, furnish, install, test, and commission the system. Installing the new system meant mounting radio transmitters on the trains, and wayside. The Canarsie Line CBTC architecture incorporates an STD/PS.

The deployment of CBTC was coordinated with procurement of R-143 cars, which were delivered as CBTC-ready cars, but had entered revenue service approximately one year before the CBTC equipment was delivered and installed. This CBTC "readiness" involved the provision of space, mounting brackets, power capacity, wiring, and cables. By the end of the project, an additional 20 R-160 four-car train units were also equipped with CBTC. Currently, the service on the Canarsie Line is supported by 59 CBTC equipped train units.

The Canarsie Line's CBTC system was commissioned and approved for revenue service by late 2006, making it the first brownfield CBTC project to be deployed on a North American mass transit system. Canarsie Line's quick facts:

- Award date: December 1999
- First revenue service date: 2006
- Last revenue in-service date: 2010
- Secondary Detection Method: track circuits

The modernization of the Flushing Line started in November 2012 and, at the time of writing this report, the anticipated completion date is planned for the second quarter of 2017. The Flushing Line (7) provides both local and express service (express service only during peak hours and in peak direction) between the Main Street Station in Flushing, Queens and 34th Street – Hudson Yards Station in Chelsea, Manhattan. This is a 10.8-mile long, underground and elevated corridor consisting of two and three tracks, featuring 22 stations and 6 interlockings. The 7 Line is one of NYCT's busiest lines in terms of frequency, with more than 620 one way train trips each day, and more than half a million riders on an average weekday.

The deployment of CBTC on the Flushing Line has been coordinated with the purchase of the new R-188 cars for the A-Division. The 92 train units, configured as five- and six-car units, came equipped with CBTC. Prior to signal modernization, the service on the Flushing Line was limited to 27 trains per hour, given the constraints imposed by the legacy signaling system and limitations at the Times Square terminal. However, the combination of CBTC and recent line extension (from Times Square to 34th Street – Hudson Yards station) allowed an increase in service by two additional trains per hour, or a 7% increase in capacity. Flushing Line's quick facts:

- Award date: June 2010
- First revenue service date: 2017
- Secondary detection method: track circuits

Both Canarsie and Flushing Line CBTC systems are integrated with an STD/PS to allow mixed-mode operation of CBTC equipped trains and operation of unequipped trains in CBTC territories using signal protection. The CBTC and STD/PS are treated as one integrated train control system, with no conflict and/or arbitration between the CBTC and STD/PS functionality during failures or degraded mode operations. Additionally, the STD/PS is also used to provide broken rail detection.

When traveling through the CBTC territories, CBTC equipped trains can operate in several modes including ATO, ATP Manual, and Yard mode. To enable an additional degree of protection, there are several (degraded) operating modes available for operations that include handling of CBTC subsystem failures. When in Yard mode, for example, the CBTC enforces safe operation through power-operated track switches installed throughout the Canarsie and Corona yards.

When traveling within CBTC territory under failure conditions, the CBTC equipped trains can be moved and operated using conventional wayside signaling, with the onboard CBTC equipment set to one of the degraded operating modes, thereby minimizing the adverse impacts on the line's service.

Though equipped by two different CBTC suppliers, both Canarsie and Flushing CBTC systems feature the following:

- ATO and manual operation under CBTC supervision are possible
- CBTC coverage in the yard
- Brownfield projects (CBTC added to wayside signaling which remains as STD/PS)
- CBTC communications between wayside and carborne using 2.4 GHz cellular radio on the Canarsie Line and 2.4 GHz Wi-Fi on the Flushing Line.

12.3.3 Legacy System

NYCT uses conventional wayside signaling with track circuits for detection and mechanical train stop enforcement of signals. Trains are operated manually on wayside signal authority.

12.3.4 Secondary Train Detection and Protection Systems

As part of the technology assessment, it was recommended to retain the track circuits not only as a method of detection for the STD/PS, but to provide protection for non-equipped revenue cars, and work fleets. Retaining the track circuits, though modified into larger blocks, and integrating them into CBTC offered a fallback system which allowed minimal interruption of revenue service in cases of CBTC, carborne, or wayside failures. The STD/PS is also used for detection of broken rail conditions. The use of axle counters was not considered, given prior NYCT difficulties with them in the 1990s.

There are some fundamental differences between STD/PS used on the Canarsie and Flushing Lines. Historically, and before the CBTC deployment, the ridership on the Canarsie Line was low compared to the rest of network, with prediction of no significant future increase, which in turn influenced some of the early decisions concerning the specifics (capacity) of STD/PS as part of CBTC. However, the ridership numbers on the Canarsie Line have increased drastically over the past 10 years. Given those early decisions, most block signals north of Broadway Junction were removed, leaving larger blocks as part of the STD/PS design to handle failures. On the other hand, all the block signals south of Broadway Junction were left intact to accommodate transfer of non-equipped trains between yards and other routes. Given the larger block size, any train failure north of Broadway Junction and subsequent recovery leads to a degraded revenue service (larger headways). There are plans, however, to introduce additional signals to reduce the size of the blocks north of Broadway Junction.

The ridership on the Flushing Line is large compared to that of other network routes and thus the fallback capabilities were designed to support the CBTC-equivalent headways. STD/PS is designed for about a 5-minute headway.

Also, the Flushing Line features much narrower platforms than Canarsie's, for example, and the fallback system of shorter headways is needed to mitigate the platform overcrowding in case of CBTC failures.

Track circuit blocks are often longer on the CBTC lines than on other routes. To facilitate migration, and in particular, during testing phases, some of the track circuits' boundaries were kept the same, where one single track circuit replaces several previous track circuits.

The Canarsie and Flushing Lines feature relay-based interlockings, with few exceptions for processor-based interlockings. Most the interlockings were renewed and brought up to NYCT CBTC standards before the deployment of the actual CBTC project.

12.3.5 Feedback on the Deployment

Deployment of the Canarsie CBTC involved various intermediate steps. In general, the details of the migration plan evolved as the project progressed, but the overall core cut-over strategy has remained intact: the legacy and new systems needed to work together during the intermediate stages, in which the non-equipped trains would progressively transition into the CBTC equipped fleet, and until such time when the new control system would be able to take control over the line.

Disruptions to passenger service during the installation, testing, commissioning, and early service operation of the new system were to be kept to a minimum. To achieve this, the legacy track circuit system had to be retained to ensure train detection and protection for both non-equipped and CBTC equipped trains. Hence, existing signals, and in some cases the addition of new ones, were used to facilitate the deployment. Eventually, signals and other assets used to support the cut-over phases were removed. The approach allowed integration of CBTC on a per-section basis and allowed mixed-mode operation until gradually all trains were CBTC operational.

This approach also involved an option to isolate CBTC from the relay-based interlockings. For example, the Zone Controller outputs were disconnected in the relay room until CBTC was commissioned. For testing purposes, the specific Zone Controller outputs could be connected to validate and stress the system. NYCT's Zone Controller outputs are grouped on a per-track basis, so that individual tracks can be tested, thereby minimizing impact on passenger service.

As the Canarsie Line's CBTC was capable of mixed-mode operation, the deployment and equipping of the new R-143 cars was handled in gradual steps. Not all trains serving the line were equipped prior to the start of CBTC operation. Additionally, to standardize future CBTC carborne interfaces, the R-143 carbuilder and all potential CBTC suppliers had to set and agree upon carborne CBTC interfaces that could accommodate use of CBTC equipment from any of the CBTC suppliers. In the end, the main differences in the system architecture between the CBTC suppliers was in the number and the type of positioning/odometry sensors, i.e. tachometers, speed sensors, Doppler radars, transponder interrogator antennas, etc.

12.3.6 Feedback on Operation

Wayside Zone Controllers are installed in technical rooms along the route, and feature full redundancy with overlapping coverage to help mitigate failures. In the event of double Zone Controller failures, i.e. complete loss of redundancy, the system is designed to default to STD/PS. In case of double Zone Controller failures on the Canarsie Line north of Broadway Junction for example, the system would switch over to an absolute block protection with no more than one train per interstation. Whereas in case of failures south of Broadway Junction, the system would switch over to STD/PS, and train movement would resume under the secondary train control protection. Double Zone Controller failures on the Flushing Line are handled by switching to STD/PS. In general, double Zone Controller failures are an extremely rare occurrence.

The NYCT CBTC system features a specific function which is used to mitigate the impact of secondary system failures to the CBTC operation. This function is called Restricted Authority (RA). In case of failures involving track circuits, signals, or train stops, or in case the status of equipment becomes unavailable to the CBTC system, the ATS operator at the control center can issue the RA command which allows CBTC trains to continue operation over the failed equipment. Trains operating under RA can only be operated in manual mode under CBTC supervision and can only move at restricted speed over the affected area.

Another NYCT-specific feature is civil speed protection used to handle cases of communications loss between carborne and wayside Zone Controller, or complete Zone Controller failure but otherwise healthy Carborne Controller (i.e. train localization is valid). Though an extremely low probability event, under such circumstances, the system can operate using the STD/PS with full civil speed protection enforced by carborne CBTC.

Onboard Communications Units are installed on each train car and feature full redundancy. In the event of double Carbone Controller failures, the system drops out of CBTC and applies the emergency brakes. Though a rare occurrence, a train with CBTC failure which cannot be restored back to CBTC is switched over to Restricted Manual mode, under which train speed is limited to 10 mph, or to bypass mode which has no speed limitation. The affected train can then be moved under STD/PS. There are, however, frequent cases where CBTC issues or operational events result in an emergency brake application, but following a quick recovery procedure, the train can resume operating in CBTC.

12.3.7 Feedback on Maintenance Fleet

The NYCT work cars are not equipped with CBTC, and their movement on the CBTC equipped lines is handled by STD/PS. As part of the long term planning, NYCT Subway intends to incorporate a degraded version of CBTC tracking of work trains. Currently, defining the length of the work train is the single largest problem as NYCT utilizes different train lengths.

Two out of four Track Geometry Cars (TGC) are the only non-revenue trains currently equipped with CBTC. These two TGCs have full CBTC capability except running in ATO mode. Equipping the TGCs was part of the project following the Canarsie Line CBTC. TGCs frequently run over the entire network, and as such will likely require future upgrades as the agency moves forward with the CBTC program on other routes.

12.3.8 Feedback Regarding the Broken Rail Issue

NYCT Subway practices the same broken rail inspection program across its network, whether CBTC equipped or not. This consists of visual inspection every 30 days and ultrasonic and thermal imagery inspection every 90 days. The inspection program proved to be efficient and it has not needed much optimization over the years. In addition, NYCT Subway maintenance personnel perform regularly scheduled maintenance of both running rail and track circuits, which helps identify significant portions of compromised rail.

12.3.9 Conclusion

Key takeaways from this case study:

1. NYCT deployed its first CBTC project on the Canarsie Line. Although defined as a pilot project, the Canarsie CBTC had achieved multiple objectives, including re-signaling of the line, development of new acquisition processes to manage high tech projects, and development of interoperability requirements for future CBTC projects.
2. Experience gained on the Canarsie Line project, including proof of CBTC architecture featuring a track circuit based secondary system, was later carried over to other lines and subsequent CBCT projects.
3. The mixed-mode operations requirement is the primary and essential driver for STD/PS. It also serves to facilitate transition to CBTC and intermediate cut-overs over different geographical sections, and allows the same level of throughput as before CBTC. As a secondary benefit, the STD/PS also acts as a fallback system to minimize service disruption in cases of failures on a very busy network.

4. On the Canarsie Line, the STD/PS is capable of supporting operation of non-equipped trains (running in degraded service) and handling troubled CBTC equipped trains, but not full revenue service in these cases.
5. Historically, NYCT has had good experience with the use of track circuits, and therefore they were selected for STD/PS. Also, keeping the same type of equipment helped facilitate the transition to CBTC.
6. A Restricted Authority function allows continuing CBTC operation at restricted speed over failed STD/PS equipment such as track circuits, train stops, and signals.

NYCT decided to have a back-up system in their CBTC project and to keep track circuits as the method of detection. The high ridership was the main reason to have a back-up system. The agency is familiar with track circuits and had no issues with them so they were kept in the new signaling system.

Even though the CBTC architecture with track circuits, train stops, and signals as fallback is the same on both CBTC lines, the depth of the STD/PS is not the same on both lines. It is not even the same on all parts of the Canarsie Line. It should also be noted that interlocking and CBTC projects are kept separated. The NYCT CBTC specification is compatible with full STD/PS capable of revenue service headway and with lower levels of STD/PS. This feature allows NYCT to adapt depending on the area and to modify the STD/PS as needed in the future.

12.4 Port Authority Trans-Hudson Case Study, Positive Train Control

12.4.1 Port Authority Trans-Hudson (PATH)

The Port Authority Trans-Hudson (PATH) is a heavy-rail rapid transit railroad which provides interstate transit service between Manhattan in New York City and surrounding New Jersey municipalities. PATH is a subsidiary of the Port Authority of New York and New Jersey (PANYNJ), a regional bi-state authority of New York and New Jersey which oversees the region's intrastate transportation infrastructure.

PATH operates a 24/7 service over four interwoven lines, using 350 Kawasaki Rail Car Inc. (KRC) cars configured in seven- or eight-car trains, depending on the line. The 14-mile-long system features 13 stations, tunnels under the Hudson River, elevated and at grade tracks, carrying on average of about 250,000 passengers per day. The four lines share common tracks and junction points, which complicates junction management. On board the train, there is one Train Engineer responsible for driving the train and one Train Conductor responsible for all other tasks, including door operation and passenger interaction.

Though a rapid transit system, PATH is subject to FRA rules, including 49 CFR Part 236, as well as the Rail Safety Improvement Act (RSIA) of 2008, including the mandate to deploy Positive Train Control.

Recently delivered PA-5 cars were designed as a CBTC-ready fleet to accommodate installation of a CBTC system.

12.4.2 Background of the CBTC Project

PATH was preparing to replace its aging signaling system (which was nearing its useful service life and becoming difficult to maintain due to obsolescence of parts) with CBTC technology when the FRA issued the Positive Train Control mandate. CBTC includes the main Positive Train Control (PTC) requirements and it was agreed with the FRA that CBTC was going to be used for meeting the PTC mandate. In December 2009, PATH awarded the signaling modernization contract to a consortium led by Siemens Mobility to install CBTC, including the ATS system at the control center.

PATH project summary:

- Award date: December 2009
- First revenue service date: Expected in 2017
- Entire Line under CBTC: Expected in 2018
- Secondary detection system: track circuits
- Secondary protection system: signals with overlapping control lines and train stops to enforce signals, implemented with processor-based interlockings integrated with CBTC
- Signaling system supplier: Siemens Mobility

12.4.3 Legacy System

The legacy system is based on fixed-block wayside signals enforced by mechanical train stops. Train detection is achieved using track circuits. Several types of signals are used to govern interlockings, provide train separation and enforce train speed at certain locations through timer logic. All switch machines and train stops are electro-pneumatic. All vital circuits are relay-based, except those between the World Trade Center and Exchange Place. These were changed to processor-based circuits after the September 11, 2001 attacks on the World Trade Center station caused severe damage to that portion of the system. Non-vital circuits are a mix of relays and processors. The performance of the legacy signaling system can meet the current demands with trains as close as 2 minutes apart.

Traction power is supplied by a covered third rail at a nominal 650 VDC. Track circuits use alternating current and operate at various power frequencies: 25 Hz in the tunnel portion using the original Hudson & Manhattan Railroad 25 Hz signal power distribution system; 60 Hz for newer installations; and 91-2/3 Hz in the outdoor portion to avoid harmonic interference from the adjacent Northeast Corridor. Most track circuits are of the double-rail type with impedance bonds.

12.4.4 Secondary Train Detection and Protection Systems

PATH has selected the new signaling system with a full STD/PS capable of off-peak revenue service on the entire system in both directions. The secondary detection and protection system uses track circuits and wayside signals, which are present at interlockings and in between interlockings for train separation.

Two different types of track circuits are used: jointless audio frequency (AF) track circuits and power frequency (PF) track circuits. AF track circuits avoid the necessity to install and maintain insulated joints and impedance bonds. Since jointless track circuits could not be implemented everywhere, PF track circuits are also used, mainly at interlockings. One of the reasons to maintain track circuits is that PATH is under FRA jurisdiction and the FRA requires broken rail detection by track circuits.

The two main reasons for requiring a full secondary system is the need for a fallback system and caution in the implementation of a new technology. The reasons for the caution toward CBTC could be that at the time of selection, there was only one heavy-rail CBTC project in the entire country—the NYCT Canarsie Line project—and there was not enough data to attest to the availability and reliability of such a system.

12.4.5 Feedback on the Deployment

Deployment of the CBTC system on the PATH network has proven to be much more challenging than expected. There are several reasons for this, but one related to the case study is that the new secondary system did not replace the legacy signaling system in kind. The block design and the signaling principles were completely renewed during the project. The new system was designed with fewer signals and fewer track circuits than the legacy system to optimize installation and maintenance costs.

The deployment is being made section by section on the network. On the first section, almost all signals were kept to mitigate early CBTC failures. However, on other sections, some signals were removed.

Equipment for all trains will be installed before commissioning the first section.

12.4.6 Feedback on Operation

At the time of the case study, CBTC operation in revenue service has not started yet. However, STD/PS in the first section is in service without CBTC. CBTC operation will be possible in automatic mode and in manual mode under CBTC supervision. Both the Train Engineer and the Train Conductor will remain on board the train after deployment of CBTC.

The main yard is partially equipped with CBTC. The signaling system for most of the yard is a conventional signaling system using track circuits as the method of train detection.

The secondary system will be used to track trains with CBTC failure and work trains. Detection will be made by track circuits and the wayside signals will be able to maintain a headway compatible with off-peak revenue service.

PATH will continue to operate 24/7 with about a 30-minute headway at night. The maintenance is done mostly while single-tracking during off-peak hours.

12.4.7 Feedback Regarding the Broken Rail Issue

Because of the reasons mentioned above, including being under the jurisdiction of the FRA, PATH selected track circuits as a secondary detection system and primary active method to detect broken rails.

PATH also performs a daily visual inspection of the tracks and has recently acquired an ultrasonic inspection vehicle and handheld devices.

12.4.8 Conclusion

Key takeaways from this case study:

1. Decision to implement a full STD/PS was based in part on the availability concerns related to a “new to the United States” technology.
2. The STD/PS is capable of off-peak revenue service.
3. The secondary detection system is based on track circuits.
4. Deployment of the STD/PS turned out to be more challenging than anticipated.
5. Broken rail detection via inspection and track circuits has been considered sufficient. Recent acquisition of an ultrasonic inspection vehicle is not related to the implementation of CBTC.
6. The CBTC system will be put in service per section, with all trains being equipped and running in CBTC in one section and running without CBTC in other sections.

Though a full STD/PS capable of revenue service is more difficult to deploy and may result in more frequent minor delays, this full fallback system assures PATH than there will be no major delays because of a failed CBTC system in the future, whether it is a train with CBTC failure or failed wayside equipment.

12.5 Transport for London Case Study, CBTC

12.5.1 Transport for London

Transport for London (TfL) is an integrated transit authority for London, UK, responsible for managing major aspects of Greater London's transportation systems. The TfL's operational responsibilities include all major surface and underground transit operations involving London Overground, London Trams, Docklands Light Railway, London Underground and TfL Rail.

TfL is one of the largest and busiest transit authorities in the world, delivering 31 million journeys on an average day, with an annual ridership close to 1.5 billion passengers.

To accommodate growing passenger demands and achieve significant increase in train running capacity, the TfL rail lines required a significant overhaul and upgrades to its signaling system. CBTC was first deployed on the Docklands Light Railway, followed by London Underground's Jubilee and Northern Lines. Most recently, the Victoria Line has been converted to CBTC (different technology and supplier to that of its predecessor). In turn, the conversion to CBTC allowed for a significant increase in train running capacity (shorter headways), automatic train protection, and full ATO.

Converting an existing line from conventional signaling to CBTC can be a difficult process, and London Underground (the Tube) has experienced some challenges with this upgrade. The project was performed without interrupting revenue service. Installation and testing was done during overnight non-revenue service hours when maintenance was also performed.

This case study focuses on the CBTC implementation on the Jubilee and Northern Lines.

12.5.2 Background of the CBTC Projects at Transport for London

The primary drivers for deploying CBTC on the TfL system were:

- Improve operating headway
- Improve line capacity

Under the new signaling system, TfL can now operate up to 34 trains per hour and intends to increase the throughput to 36 trains per hour. In late 2003, Alcatel's Transport Solution Division was awarded a contract to re-signal the Tube's Jubilee Line and Northern Line. The Jubilee Line was the first to be re-signaled, with both lines using similar CBTC technology and an axle counter based secondary system. The lessons learned on the Jubilee Line experience were applied to the Northern Line upgrade. Given that both projects were brownfield types, the lines were not shut down during the CBTC deployment. Despite the enormous challenges with such an upgrade, both projects were successfully completed, and objectives of improving headway and capacity have been achieved. Following are the salient highlights of these projects:

Jubilee Line:
- Award date: 2003
- First revenue service date: December 2010
- Entire Line under CBTC: June 2011
- Secondary detection system: axle counters
- Signaling system supplier: Thales Transportation Solutions

Northern Line:
- Award date: 2004
- First revenue service date: February 2013
- Entire Line under CBTC: June 2014

- Secondary detection system: axle counters
- Signaling system supplier: Thales Transportation Solutions

12.5.3 Legacy System

Prior to CBTC, both the Jubilee and Northern Lines were using conventional signaling systems with track circuits used for detection and train stops used for signal enforcement. The trains were operated in manual mode under wayside signal authority. Operations with conventional wayside signals were similar to U.S. transit agencies such as NYCT or the Massachusetts Bay Transportation Authority.

12.5.4 Secondary Train Detection and Protection Systems

For both these projects, the secondary detection system to support the CBTC implementation was based on axle counters. On prior projects, TfL had gained experience with axle counters deployed in one depot but not on mainline tracks. Axle counters are common in the UK; Dockland Light Rail and Network Rail used axle counters on their signaling projects.

Axle counters are used primarily for:

1. Failure management: The line cannot be operated in revenue service without CBTC, i.e. with the axle counters only. Axle counters are used to track trains with CBTC failure. Operation of trains with CBTC failure is limited to 10 mph and line-of-sight since there are no signals on the wayside.
2. Non-CBTC equipped vehicles. This is limited to non-passenger, night service hours.
3. Initialization of engineering vehicles when coupled with CBTC equipped cars. The axle counters are used to determine the length of the trains by counting the number of axles. Knowing the length of the train allows the train to run under a simplified form of CBTC (no ATO operation). Axle counters are not only used for block occupancy but also for train length determination.

Location of the axle counters are as follows:

- At interlocking areas (around switches) – TfL is considering if this is necessary for future projects. Indeed, the CBTC system can know the location of the trains and would be able to lock the switches for an approaching train.
- One per station for tracking capabilities in case of failure – Tracking a train with CBTC failure is not only necessary for knowing the position of the train, but also for allowing other train operation around the zone affected by the train with CBTC failure.
- At Zone Controller boundaries for managing handoff – This is a design requirement rather than an operational requirement.

TfL considers axle counters to be reliable. However, in order not to impact operation in case of axle counter failures, TfL decided to introduce a function that gives the possibility to override axle counters under certain conditions regarding other train tracking in the area. TfL used less axle counters in the second project. For future projects, TfL will consider using even less axle counters than on the Jubilee and Northern Lines.

Signal enforcement consists of legacy train stops on the wayside. Though initially they were retained, train stops are mechanical devices prone to failure and therefore some are being removed from the system.

12.5.5 Feedback on the Deployment

The legacy system using track circuits as a secondary detection method was decommissioned after conversion to CBTC. Migration to the new signaling system was done per geographical area, one section at a time. All trains ran in CBTC mode through converted sections, and in conventional mode while operating on non-CBTC sections. This method required a manual transition on board the train when going from one system to the other. Before CBTC operation started on the first section, the entire fleet of trains was equipped with CBTC. There was no need for mixed-mode operation where one CBTC train runs among other non-CBTC trains.

Regarding installation, TfL indicated that axle counters were susceptible to electromagnetic interference generated by the traction power system. TfL uses a third- and fourth-rail system to power the train, along with traction power and negative return cables. Therefore, locations of axle counters and the layout of their cables in the field must be carefully planned with the traction power system. Also, to allow maintenance of the axle counters to be performed safely, the third rail must not impede on the space around the axle counter.

The success of the CBTC projects was made possible with a robust test strategy along with a recovery plan during the deployment of the system.

12.5.6 Feedback on Operation

TfL operates CBTC trains in ATO mode where the driver starts the train after each stop. Yards are not equipped with the new signaling system and manual line-of-sight operation is used in these areas.

Non-CBTC equipped work trains are not permitted during revenue service. When a non-CBTC equipped work train is used, it operates within a dedicated area.

Trains with CBTC failure are operated at slow speed using line-of-sight. There are no signals on the wayside. Revenue service is not possible without the CBTC system. Axle counters are used to track trains with CBTC failure and only the train with CBTC failure is authorized to move in the area.

TfL indicated that there were very few wayside failures since the beginning of revenue service of CBTC. The Jubilee Line has five wayside controllers and the Northern Line has eight wayside controllers. In US projects, wayside controller Mean Time Between Functional Failures are usually specified for about 100,000 hours, and based on discussion with TfL, the system put in place in London meets this requirement. When a wayside controller failure occurs, all trains in the area controlled by this controller are forced to stop. Rebooting a wayside controller only takes about 10 minutes and therefore these failures can be fixed quickly without causing major delays. Wayside controllers have a 2-out-of-3 architecture; if a failure on one computer occurs then the wayside controller continues operation with a 2-out-of-2 architecture until further maintenance can be performed at night when there is no passenger service.

12.5.7 Feedback Regarding the Broken Rail Issue

Detecting a broken rail after it happens using a track circuit is too late because it dramatically impacts train operation. It is important to prevent broken rails from happening to avoid such delays. In addition, based on TfL's own experience, track circuits are an inefficient method to detect broken rails. One reason cited was that a broken rail often happens when a train runs over the area and, since axles of the trains are shunting the rails, it is not possible to detect and slow down the train when passing over the broken rail.

In addition to visual inspection, TfL is using ultrasonic inspection and a longitudinal rail stress measurement program. The program is the same on all TfL lines, whether the signaling system includes track circuits or not. The rail issue detection program put in place is efficient and did not need to be optimized since introduced.

Inspections are performed mostly at night; however, some of the revenue service trains are equipped with ultrasonic inspection and other rail issue detection equipment. The data from these trains is only available when the train comes to the yard, but since inspections have the capability to detect rail flaws before the rail break, this is not an issue.

12.5.8 Conclusion

Key takeaways from this case study:

1. Secondary detection system is based on axle counters. No wayside signals are present.
2. Axle counters are deployed mostly for train failure management. STD/PS was not designed to handle wayside failure and operate revenue service.
3. CBTC availability is very good and proved that there was no need for an STD/PS capable of running revenue service.
4. Though reliable, a function to override axle counters was introduced and TfL is considering using less axle counters in future projects.
5. Protection methods such as train stops might also affect overall availability and TfL is reducing their numbers.
6. Rail issue detection through inspection has been proven to be successful.
7. The new STD/PS was not used during the transition to CBTC.

In summary, CBTC has been implemented successfully and is operated very efficiently using STD/PS, based on axle counters to handle trains with CBTC failure on both the Jubilee and Northern Lines Though already light, the STD/PS might affect the overall availability of the system and TfL is working on optimizing the number of devices.

12.6 Baltimore Metro Subway Case Study

12.6.1 Baltimore Metro Subway

The Maryland Transit Administration Baltimore Metro Subway is more than 15 miles in length, consisting of a two-track mainline with 5.5 miles underground. The system entered service in 3 phases. Section A entered service in 1983 with 9 stations, and 7.5 miles of double track. Section B entered service in 1987 with a double track extension of approximately 6 miles, serving 3 stations. Finally, Section C was available in 1996 with an underground tunnel extension of 1.5 miles of double track serving 2 additional stations. The mainline operation is supported by a single yard and maintenance facility, and an integrated central control facility that is also responsible for other light rail and police transit services. The maintenance facility has sufficient storage for all 100 railcars.

The Metro provides nearly 50,000 daily trips, operating 19 hours per weekday. Peak service is provided with 6-car trains at 8-minute headways and 9 trains in operation. Off-peak service is provided with 4- to 6-car trains at 11-minute headways.

12.6.2 Background

The MTA is procuring a replacement for the Metro system elements now beyond their 30-year design life. The replacement project includes both train control and new railcars under one contract. As both major elements of the Metro are of the same age, it was concluded that obtaining replacements under a single procurement would be the most efficient, and least risky, given that significant interfaces would best be managed under a single contract.

The MTA has decided that CBTC is the best solution for implementing a complete retrofit of the current signaling system, one that will permit a cut-over from the old to the new, and will provide a durable state-of-the-art design with a 30-year life. In addition, the system will include complete capabilities for driverless operation, where at a point in the future, when the fixed facilities have been modified to accommodate driverless train operation, the train control and train systems will be ready.

12.6.3 Legacy System

The mainline signal system consists of AF-400 track circuits and a cab signaling system supplied by Union Switch and Signal. There are more than 400 track circuits that provide detection throughout mainline and yard track. The yard, however, is not included in the AF-400 system and is provided with power frequency (PF) track circuits throughout. The yard accommodates only manual movement of trains, where the trains are limited to 12 mph with an onboard generated cab signal code, when the operator places the mode selector switch to the yard position.

The train control equipment is distributed along the mainline and yard among 17 train control rooms that include the audio frequency track circuit racks, the power frequency racks for the 8 mainline interlockings, and relay racks for occupancy status in the yard. The wayside network connects the train control rooms to central control as well as to a back-up control facility located in the yard tower.

12.6.4 Replacement CBTC System

The CBTC replacement solution will materialize in response to the performance requirements identified in the Request for Proposal (RFP). The system design need not replicate the legacy system installation approach or locations, but rather result in a system replacement best suited to the contractor's system approach. The contractor is expected to take advantage of modern communications and computing strategies that will likely minimize the amount of equipment needed, reducing installation locations and complexity. The desire to use proven technologies, minimize development costs, increase reliability and availability, and implement the CBTC project integrated with the railcar procurement is key to introducing both into service with minimal disruption to ongoing Metro passenger service.

The CBTC system implementation with accompanying new railcars will permit the new train control system to be overlaid on the alignment in parallel with the legacy system. Additionally, this includes new railcars that will only operate with the new CBTC system, while at the same time the old trains will continue operation under the legacy train control. This overlay approach will enable the new system to be fully installed and allow new CBTC equipped trains to enter service, replacing one-for-one the old trains. When the new trains have sufficiently replaced the old, the legacy train control system can be decommissioned and removed from the system. Any temporary equipment room facilities created to support the transition will be removed once the CBTC equipment is in the final space of the train control rooms.

12.6.5 Secondary Train Detection and Protection Systems

The project requires that communicating trains and non-communicating trains, including work trains, be protected. This will likely involve the use of axle counters and/or track circuits. The project does not preclude any one solution, and does not limit the solution to the above two. The requirements do not specify a level of performance in either degraded mode or when non-communicating trains are operating simultaneously with communicating trains. The focus is on protecting communicating trains, non-communicating trains, and work trains anywhere in the system; it is not to provide a back-up to the CBTC system. The protection blocks will be long and likely keyed to the interlocking locations. Although the Maryland Transit Administration policy is to not operate work trains while passenger trains are operating, the safety of the system depends on detection, and not policy.

12.6.6 Broken Rail Detection

Although the current signaling system has, as a byproduct of the design, the ability to announce a break in the running rail, it cannot reliably indicate a rail flaw prior to a catastrophic and complete break in the rail. The Maryland Transit Administration has experienced several rail fractures in 33 years of operations, but cannot recall an instance where the track circuit system indicated a rail failure, even an incident where the break was audible. To mitigate the rail flaw hazard, the Maryland Transit

Administration has included options for flawed rail detection in the Railcar and Train Control Contract. Although the track circuit approach is limited to only indicate complete rail breaks, it is one of the options permitted. The second option described in the RFP is the provision of a high-rail vehicle capable of not only inspecting the running rails of the Metro system using ultrasonic techniques, but also capable of the same inspection performance on the Maryland Transit Administration light rail system. For the Maryland Transit Administration, requiring the high-rail alternative to also accommodate the needs of their light rail provides more utility from a valuable piece of railroad equipment.

12.6.7 Conclusion

As the Baltimore Metro system replacement is in the procurement stage, the implementation of CBTC, STD/PS, and rail flaw detection have not been decided yet. With a winning bid and with a notice to proceed the technical specifics of the contractor’s proposal will begin to be finalized as part of the design review process. Nonetheless, the Maryland Transit Administration has concluded:

1. The desire to continue to track Maintenance-of-Way work trains (non-communicating) is mandatory.
2. No longer will the Maryland Transit Administration rely on broken rail detection via track circuits.
3. A proactive approach to rail flaw detection will be a part of the system replacement with the procurement of a detection system, such as ultrasonic inspection.
4. The STD/PS need not support a specific level of back-up operations performance, but rather provide vital train separation for all trains, especially non-communicating trains.
5. The overlay of CBTC and its use with only the new replacement trains, with simultaneous operation of the old trains with the old signaling system, is a viable basis for the transition and cut-over.