CBTC Upgrade Scope Definition and Implementation

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ABSTRACT

Communications Based Train Control (CBTC) signaling systems have been reliably and safely carrying passengers in revenue service for over a quarter-century. Once a futuristic, technological novelty, CBTC is now established as the latest generation of mainstream transit system control.

Today's progressive railroads find themselves compelled to consider a CBTC upgrade because of its promises of increased safety, reliability, availability and associated reduction of maintenance costs; increased system capacity using the same civil infrastructure and its ability to reduce downtime during an upgrade. But there are costs to consider. Should the full fleet be equipped or only part of it? The full railroad, including yards and depots, only the mainline or only a portion of the mainline? Is a secondary train control system needed, or is CBTC alone adequate? This paper will consider such questions.

Whatever the motivation, once a decision is made to upgrade to CBTC, and the scope of the upgrade is defined, the implementation needs to be planned carefully and executed flawlessly to manage the impact on ongoing operations, and to ensure safety throughout the upgrade process. Should a "big-bang" implementation be planned or a staged transition from old to new? If staged, should a fleet-first or an infrastructure-first approach be adopted? How can opportunities for "shadow-mode" testing be exploited to minimize system downtime and risk during cutovers? How and when should operations and maintenance staff be trained? Answering these important questions will ensure a successful "brown-field" CBTC system upgrade.

ASSUMPTIONS AND DEFINITIONS

Communication-Based Train Control (CBTC) System

Whereas a conventional signaling system determines train location using Interlocking Controllers ("Interlockings") that monitor track circuits or axle counters, a CBTC system employs Carborne Controllers (CCs) to determine train location primarily from wayside devices such as transponder tags or inductive loops. The CC typically augments this information by reading finer positioning devices such as tachometers, speed sensors, radar and/or accelerometers, and transmits fine-resolution position, speed and direction status information to wayside Movement Authority Controllers (MACs), each of which communicates with CCs and Interlockings, to collect the status of all trains and routes in its control area. The MAC uses this information to calculate stopping point commands for the CCs in its control area, in such a way as to ensure safe train separation and routing. This fine positioning capability is foundational to the achievement of CBTC's shorter-headway capabilities. The majority of CBTC systems are based on Moving-block signaling principles, which fully leverage the fine positioning capabilities of CBTC.

Functional Architecture

For the purposes of this paper, a CBTC system is assumed to provide the classical Automatic Train Control (ATC) functions of Automatic Train Protection (ATP), Automatic Train Operation (ATO), and Automatic Train Supervision (ATS), generally in accordance with the requirements of [1], summarized as follows:

- ATP functions provide for fail-safe protection against collisions, excessive speed, and other hazardous conditions through a combination of train detection, train separation, and route locking;
- ATO functions typically include automatic speed regulation, automatic programmed station stopping, and automatic door control; and
- ATS functions typically provide all monitoring, control and automation necessary to fully support and coordinate system wide train movements: this includes tracking of trains during normal operations and facilities to support degraded service due to external conditions such as equipment failure or environmental factors; the adjustments can be to the performance of individual trains to maintain schedule, or corrective action to be taken by Control Center staff.

Physical Architecture

In addition to the functional components (ATS/ATP/ATO), the CBTC can also be organized by geographical location. CBTC equipment is typically located in the Central Office, in Station Equipment Rooms, at the Trackside and aboard the rolling stock.

Central Office equipment is typically that associated with ATS functionality, and inclusive of the main Human-Machine Interface for System Operations.

Station Equipment Room equipment includes communication backbone switches, MACs and

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Interlockings (these last two are sometimes combined into a single, dual-purpose "Zone Controller" or "ZC").

Trackside equipment includes transponder tags/balises/loops, switch machines, radio transceivers and transit signals (if required to support Secondary Train Control (STC)).

Carborne equipment comprises a processor-based controller(s) and its peripherals, capable of determining train position, limiting train movement and supporting Train-to-Wayside Communication (TWC) with the MAC and ATS.

Movement Authority Controller

The MAC is a computer-based ATP controller, typically located in equipment rooms in the Central Office and passenger stations hosting interlocking equipment, which is responsible to:

a) Monitor the location and status of all communicating trains in its control area;

b) Monitor switch position and route locking information received from the Interlocking;

c) Monitor the status of other wayside elements in its control area (e.g. Platform Edge Doors, Platform Emergency Stop Buttons);

d) On the basis of this status, provide each CC in its control area with a Movement Authority Limit (MAL), up to which the train is authorized for safe travel; and

e) Safely transfer trains into and out of its control area.

The consolidation of MAC and Interlocking functions in a ZC, to minimize hardware, is usually undertaken only where no STC is to be provided, since common hardware failure modes in the primary and secondary systems is not a concern in that case.

Carborne Controller

The CC is a computer-based ATP and potentially ATO controller, installed on the rolling stock. The CC is responsible to:

a) Monitor the configuration, location, speed, direction and other status of its host train, and report these to the MAC;

b) Control propulsion, braking and door systems to ensure safe train operation, including containment of travel within any speed limits and the MAL;

c) Provide cab signaling directions to the driver for attended modes; and

d) Control propulsion, brake and door systems according to commands from the MAC and/or ATS, to optimize speed profiles and dwell management, for systems providing ATO.

If STC is to be included, train stop functionality and associated peripheral hardware may be integrated into the CBTC CC, or may be hosted by non-CBTC equipment. Train stops implemented for speed or train spacing purposes may need to be disabled for automated CBTC trains, which may be subject to different constraints than non-CBTC trains.

Train-To-Wayside Communications

The TWC component of the CBTC provides high-availability, low-latency (i.e. time sensitive), continuous communication between CCs and MACs. This communication may or may not be safety-critical in itself, depending on how much supervision is undertaken at the application level between the MAC and CC. Some TWC systems are configured to account for the physical location of CCs, whereas others adopt a flat architecture, having knowledge only of radio IP addresses, leaving it to the CC and MAC alone to manage location-related data.

TWC components include radios and antennas communicating in free space. The antennas may incorporate point-to-point communications or a leaky conductor style medium installed along the guideway. They may also include switching, routing and authentication and/or encryption equipment, depending on the sophistication of the TWC.

Primary and Secondary Train Control

CBTC will assume the role of the primary train control system, having vital/safety critical elements designed and implemented in accordance with fail-safe design principles and internationally recognized standards; and designed to achieve high levels of system availability through component selection, appropriate levels of equipment redundancy, and the use of local and remote diagnostic facilities, generally in accordance with [2].

A STC System is typically a conventional signaling system that supplements the CBTC system, in order to provide a level of ATP functionality for trains or Maintenance of Way (MOW) equipment that are:

- Not equipped with carborne CBTC equipment; and/or
- Operating with partially or totally inoperative carborne CBTC equipment; and/or
- Operating within an area of track with partially or totally inoperative wayside CBTC equipment.

The several, progressive levels of sophistication for the design of STC systems are summarized as follows (for a comprehensive discussion on the extent to which STC should be included in an CBTC upgrade, refer to [3]):

- Level 0: Either no STC at all, or possibly inclusion of switch position indicators used to supplement control operator directions for route traversal, without enforcement;
- Level 1: Switch deadlocking: power to a switch machine is interrupted when the over-switch block, bounded by axle counters or track circuit boundaries located at or outside the switch's fouling points, is not assured to be vacant;
- Level 2: Level 1 + trackside or cab signal indication to the train driver that the switch is locked for safe traversal, possibly including full switch locking such as route locking, approach locking, track locking and flank protection Interlocking functions;
- Level 3: Level 2 + scope to include also non-switch areas, in a contiguous portion of the entire mainline guideway;
- Level 4: Level 3 + functionality to safely stop a train by the use of mechanical, electromagnetic or electronic train stops, should the train (a) violate a wayside or cab signal, or (b) violate a speed limit supervised by successive train stops.

Mainline Train Operating Modes

CBTC Systems readily support fully bidirectional running capability, due to their functional independence from wayside signals. Automatic Train Operation (ATO), by which the CBTC controls the train's speed profile, is usually included in the CBTC configuration to optimize headway reduction (hence optimal infrastructure exploitation). ATO typically includes a subset, in order of decreasing automation, of the following operating modes:

- Unattended train operation (UTO)
  [GoA4 ("Grade of Automation" [4]): no driver required on train]
- Driverless train operation (DTO)
  [GoA3: train attendant controls doors and undertakes recovery operations]
- Semi-automatic train operation (STO)
  [GoA2: driver in cab controls doors and recovery operations]

In addition to ATO modes, the following modes may be supported by the CBTC:

- Protected manual operation (ATP-M)
  [GoA1: driver controls all motion, subject to ATP enforcement]
- Restricted Manual
  [Manual operation with speed only restricted, by CBTC or other carborne equipment]
- Full Bypass
  [Train operation is protected only by driver's adherence to operating rules, sometimes speed-supervised by systems outside CBTC, such as Propulsion]

CBTC may also include an explicit indication of locations where CBTC operation is permitted (i.e. where the driver is authorized to follow the CBTC display on the train, sometimes implemented as a "lunar" aspect or "St. Andrew's Cross" aspect on the wayside signals). It may be possible to command the CBTC to prohibit the use of some modes during exceptional circumstances where a heightened need for driver vigilance is called for (e.g. poor weather conditions, or suspicion of unauthorized guideway access).

Shadow-Mode Testing

For the purposes of this paper, Shadow-Mode Testing is defined as an early mode of site testing for a CBTC upgrade (brownfield), whereby some or all of the train localization and TWC infrastructure is fully commissioned prior to commissioning of the rest of the CBTC, and a subset of existing rolling stock is equipped with carborne CBTC equipment and returned to revenue service under the ongoing control of the existing signaling system.

For shadow mode testing, the CC is configured to watch the train's progress along the line, gathering information about positioning and communications effectiveness, and reporting this to a subset of the MACs. It is configured so as not to interfere with the safe operation of the train, which continues under the protection of the existing signaling system. The benefit is the relatively unobtrusive gathering of data representing where the CC "sees" itself, as the train traverses its route, based on e.g. transponder tag position and route information received from MACs.

The goal is to capture data during revenue service, and then to download it for early-stage offline analysis, which can include statistical reliability indications. Depending on the sophistication of the TWC system, this download of data may be supported remotely (e.g. WLAN or WiFi link) or locally (e.g. USB port on the CC).

DECIDING BETWEEN CBTC AND CONVENTIONAL SIGNALING

Some of the factors that a transit authority has to consider when deciding whether to upgrade its signaling system to CBTC include the following:

- What are the business needs driving the re-signaling program? Is it purely to maintain the signaling system in a state of good repair, or is there a business case for a step-change increase in passenger carrying capacity?
- Is the signaling system upgrade being considered as a stand-alone signaling project, or is the re-signaling being considered as one element of an overall system upgrade program also including, for example, new vehicle procurements and upgrades to the operations control centre?
- Is the transit authority prepared to enhance other, non-signaling systems, such as power supply and tunnel ventilation, to accommodate more trains in high-density sections of the railroad, or station/bus interchange redesign to support the greater passenger flow (i.e. eliminating the next bottleneck, once the signaling system has been removed as the primary constraint on headway)?
- Are there physical, track layout constraints (e.g. direction reversal crossovers placed too far ahead of reversal platforms) or unique fleet characteristics (e.g. particularly long stopping distances) that might negate the headway benefits of CBTC?
- Will automation be seen as a threat or opportunity by employees and potentially labor unions? The enhanced safety and repeatable performance associated with CBTC can be seen as protecting drivers from incidents and from disciplinary actions, but it can also be viewed negatively, rendering some driver functions as redundant, depending on the nature and history of the property. As with any technology evolution, employee and union perspectives and expectations must be carefully managed to ensure a successful CBTC upgrade.
- Is the option to retain conventional signaling really less risky than CBTC? During an upgrade of one conventional signaling system with another, especially where different suppliers or even different divisions of the same supplier are involved, can lead to long service outages where an overlay solution is not feasible and outright replacement of hardware is required. CBTC solutions can sometimes co-exist with already-present conventional signaling solutions to facilitate a smoother transition throughout the upgrade.
- Beyond the actual commissioning of the CBTC infrastructure, are we prepared to roll out proper training, to ensure that we leverage the full benefits of CBTC? (CBTC can be operated in such a way that it provides no better service than a conventional system.)
- If STC is to be implemented, is there support for the potentially higher (not lower) maintenance costs of a hybrid system, in the interest of obtaining the performance advancements associated with CBTC?

Philosophical Differences

CBTC systems require the continuous transfer of status information from train to wayside, and of command information from wayside to train. To safely manage all trains in its control area, the MAC must have current information at all times. A positive side effect of this aspect of CBTC is that this information is also immediately available to the ATS controller(s), as it undertakes its mission to optimize fleet performance.

Moving Block (MB) CBTC systems take a vehicle-centric approach to the generation of MALs, as compared to the guideway-centric approach of conventional, Fixed Block (FB) signaling systems. This vehicle-centric approach, coupled with the finer position resolution of CBTC has the potential to significantly reduce operational headways, primarily through the reduction of safety buffers ahead of each train, as illustrated in Figure 1.

In all signaling systems, the safe train separation buffer is calculated based on worst case vehicle braking performance in the context of trackwork features and other obstructions supervised in a defined region. The practical difference between FB and MB is the following:

- For FB, the calculated safety buffer is implemented by selecting a minimum discrete number of fixed-length signaling blocks which must be maintained in front of the train. Hence, the resolution of the safe stopping point command is the length of the signaling block, and a block is deemed fully occupied if any axle of the train falls within the block boundaries, either by traversing an axle counter or shunting the track circuit associated with the block.
- For MB, the buffer is represented by a parameter that is calculated dynamically, based on train location and often speed, and whose resolution is limited only by software constraints. Some CBTC systems can calculate train location to a resolution (although localization precision is more coarse) as small as 1 mm, with the result that the safety buffer is virtually continuous.

The more dynamic and higher-resolution MB safety buffer adjusts to favorable conditions by reducing train spacing, thereby supporting more frequent service. In some CBTC system designs, the buffer is calculated offline for each location and the worst-case speed profile, then applied for all speeds, while in others, it is calculated dynamically using train speed as an input parameter.

In terms of capacity, a fixed-block system can, in principal, approach the performance of a moving-block implementation. However, this is usually cost-prohibitive, since reduction of block lengths naturally increases the number of blocks, which increases Interlocking complexity, and quantities of the wayside hardware required to implement the block boundaries.

CBTC offers greater operational flexibility, through its inherent, economical support of bidirectional operation. The high cost associated with adding signals and associated logic to a FB Interlocking in support of reverse-running does not apply for CBTC. Whereas with FB, transit Properties often have to limit bidirectionality to only certain locations, with CBTC, the difference amounts mainly to an additional use case that the software must accommodate, so it can be implemented universally.

One of the other performance benefits of a moving block solution is that it can more rapidly recover from a system disturbance, both in terms of implementing temporary degraded service and in terms of restoring full service, so that overall service reliability is improved. This factor is further enhanced for driverless systems for which the logistical challenges associated with driver deployment do not apply.

Hardware Differences

The hardware used in today's CBTC system components is far less costly than that of early CBTC systems. With the proliferation of high-performance computers and data communication networks, hardware is no longer the constraint that it used to be. The main costs associated with a CBTC upgrade are now the following:

- Engineering effort required to adapt an existing product to a new Property, in compliance with its unique specification: almost every CBTC system is bound to have unique interfaces such as with vehicle systems and adjacent territories like yards, but functionally speaking, the closer the CBTC design for a new application resembles the last one implemented by the supplier, the lower the upgrade project's risk;
- Compliance with local codes and standards, if they are more onerous than previously encountered;
- Accommodation in software of new hardware or operating system platforms that may be imposed due to end of life constraints;
- Carborne / recurring hardware, as compared to wayside or central hardware, especially for larger fleet sizes; and
- Development and testing of software (beware of regression testing associated with the above rework).

CBTC introduces certain wayside positioning and communication hardware such as transponder tags/balises/loops, radios, antennas and associated cabling. The cost to purchase, install and maintain these devices is far less than that associated with the signals, train stop devices and track circuits or axle counters required for conventional systems. The savings are of course reduced and may actually be reversed where STC is implemented, especially if the STC configuration is particularly complex or sophisticated.

Operating Concept Differences

Apart from capacity improvements due to shorter headways, the bidirectional nature of CBTC systems, in terms of both train movements and data communication, provides the Central Control staff with more current status information, the ability to command a train directly and increased flexibility in dealing with traffic disturbances. All CBTC-equipped trains in the system are in continuous communication with the Central Office (each commonly reporting status in the range of once per second), so the mimic display can provide a more continuous, less granular representation of their locations. Commands sent to a CBTC train such as speed reductions or stop orders can be immediately transmitted even when the train is between stations, due to the continuous data link. Trains can be easily routed around an area of track suffering from a blockage, even when it depends on reverse-running. With the dramatic reduction in signaling system constraints, limitations on operational flexibility are reduced mainly to trackwork geometry.

The repeatability of DTO and UTO functionality, and to some degree that of STO, removes the uncertainty associated with driver performance, allowing more predictable operation and hence more finely-tuned schedules with less inherent contingency time. Today's ATS systems often include schedule development, and schedule and headway regulation and simulation capabilities. Some even include "green" energy conservation functionality such as the synchronizing of train arrivals and departures to optimize rolling stock regenerative braking capabilities. These can be fully leveraged by the flexible nature of CBTC.

Effects on RAMS (Reliability, Availability, Maintainability & Safety)

The main reliability improvement provided by CBTC is found in the simple reduction of hardware quantities in the system. Assuming appropriate component selection, the fewer components that can fail, the better the reliability of the system will be. Highly-competitive computer and data communication markets have produced cost-effective, high-quality, high-reliability network equipment and computers that can be used in CBTC systems, unlike the components of conventional signaling systems, many of which continue to use high-cost proprietary components. The omission of signals and trackside hardware associated with axle counters or track circuits improves system reliability. It is important to pay attention to the trackside devices associated with CBTC too, however. For example, wayside radios and transponder tags or loop cables, need to be sufficiently robust for the harsh physical and electromagnetic environment. Transponder tags are not all created equal: some are powered by the interrogation beam from the carborne reader, while others are powered by batteries that require periodic replacement to maintain their function or accuracy. Some TWC configurations have radios and antennas only at trackside, while others also include integrated network switching devices.

Enhanced reliability of the basic system with less hardware also in itself provides an availability boost, but this can also be supplemented with operational redundancy, such as 2-out-of-3 or 2-times-2-out-of-2 hardware configurations, to improve availability, with a marginal increase in hardware. This can reduce the probability of encountering a service-impacting failure to very low levels, compared with all but the most costly conventional signaling systems. Synchronization of multiple processors is complex, however, so any development of such functionality (as opposed to off-the-shelf application of an existing design) during the project should be closely monitored.

With less wayside hardware, especially at track level (signals and track circuits or axle counters), CBTC is also inherently more maintainable than conventional signaling. Data networking equipment can be housed in equipment rooms with Interlocking and MAC hardware, with only wayside radios, transponders/loops and switch machines located at trackside. The main savings are in the maintenance of signals and trackside hardware associated with axle counters or track circuits.

CBTC systems enhance operational safety by the following means:

- Reduction of the amount of hardware that can fail, generally leading to a lower system hazard rate;
- Incorporation of checked-redundancy, and design and code diversity to minimize single points of failure;
- Simplification of the system design (most incidents are the result of many things going wrong, not just a single equipment failure, so more complex systems inherently present more hazard potential); and
- Simplification of the actions required to manage uncommon events.

DETERMINING THE UPGRADE SCOPE

Once the decision has been made to undertake a CBTC upgrade, there are a number of scope questions that will need to be answered:

- What vehicle operating modes need to be supported?
- Should the entire fleet be CBTC-equipped, or only part of it? Do maintenance vehicles need to be equipped?
- Should the full railroad be equipped, including yards and depots, or should the scope be limited to only the mainline or a portion of the mainline?
- What constraints, if any, apply to the TWC?
- Is STC required, or will CBTC alone be adequate?

Vehicle Operating Modes

The decision of which modes of operation need to be supported is complex, and is based on technical, political and human-factors considerations. In terms of efficiency and cost, more automation is generally better for a number of reasons. However, most CBTC upgrades are undertaken for existing properties, and funded by governments that must be able to clearly demonstrate they are bringing value for their citizens.

The benefits of CBTC can be best leveraged by UTO and DTO, which provide the greatest consistency and flexibility of operation, resulting in payroll reduction and diminished effects of driver error, performance and personal needs (e.g. shift lengths and break schedules). The consistency of driverless operation allows optimization of system performance, which in turn provides the highest passenger transfer capacity, and passenger satisfaction. Conversely, with UTO and DTO, no driver may be present to detect and react to anomalous conditions on the track ahead of the train (e.g. a passenger falling off the platform or a car driving through a fence and falling into the guideway from an overpass). Protection against such intrusions requires the implementation of additional systems, such as Platform Edge Door Systems (PEDS) and/or Guideway Intrusion Detection Systems (GIDS) of various types (some technologies in service around the world include electro-mechanical, light-based, radar-based and video-based; for more detail, refer to [5]).

Politically, despite the more than 25 industry-years of UTO in revenue service (Vancouver SkyTrain first launched UTO service in 1986), some locales may still be reluctant to embrace UTO and DTO. Whether the local climate is optimistic and ambitious or particularly risk-averse may therefore also affect the decision whether or not to implement UTO or DTO.

For these reasons, some properties elect to support only STO. This mode retains the driver to detect such hazardous conditions, and the repeatable speed profiles of DTO and UTO, but is subject to driver delays such as reluctance to trigger the start of operation (e.g. commanding doors closed or activating a Start button), and staff scheduling constraints, and of course it lacks the potential payroll savings of more automated modes. It also requires the provision of an expensive, ergonomic driver's cabin at either end of a basic train unit, which consumes space that could otherwise be used by passengers: UTO and DTO trains can be equipped with relatively simple hostling panels that can be folded out of the way when not in use.

All three of the above require a fully exclusive Right-Of-Way. If that is unavailable (e.g. LRT tracks running in the context of an automobile roadway, with potential shared access with vehicular traffic), then the highest level of automatic operation will be limited to Protected Manual, due to the highly unpredictable nature of the operational environment. This mode ensures safe train separation and route locking, but is operationally far less predictable than more automated modes.

Coverage of the Fleet

Many transit authorities considering a CBTC upgrade have been in service for many years, and consequently have expanded their fleets with new rolling stock models, perhaps many times over the years. Defining and integrating the on-board interface for ATO is a significant challenge in any case, and can be further complicated by variations in connectivity and behavior among vehicles. However, a decision to exclude a portion of the operational fleet from the CBTC should be made carefully, for the following reasons:

1. Operational optimization in a short-headway condition can suffer from a "weakest-link" phenomenon, such that the flow of all other traffic will be affected by one under-performing non-CBTC-equipped vehicle; and
2. If not even ATPM mode is to be provided for older vehicles, then this may force the implementation of STC where it may not otherwise be appropriate.

If there will be no STC, then MOW vehicles will still need to be protected from the movements of automatic vehicles around them, especially if they operate on revenue track during revenue hours. This protection can be provided in a number of ways:

- For small MOW vehicle fleets, or those with captured MOW vehicles (e.g. monorails), a permanent carborne monitor can be installed on each vehicle that reports occupancy information (position, speed, direction) to the MAC, and possibly provides ATP supervision of speed and position akin to Protected Manual operation of revenue vehicles.
- For larger MOW vehicle fleets, or at properties for which MOW vehicles are not captured to the system (e.g. those furnished temporarily by subcontractors), a portable or temporary carborne monitor (e.g. on a trailer) may be used.
- In smaller systems or those with high degrees of staff discipline, strict adherence to procedures governing the definition and enforcement of work zones, for which traversal of automated trains will be permitted only in ATPM or lower mode of operation, may be adequate.

Coverage of the Line and Yards

Some transit authorities prefer uniformity of the system, so the CBTC upgrade is implemented for all parts of the system, including yards, depots, test tracks and even some maintenance tracks (other maintenance tracks such as pits must remain clear of any wayside equipment such as loops and tags). In a driverless or unattended operation, this arrangement offers the benefit of full independence from drivers, for maneuvers required in preparation for service at initial fleet launch, even from remote locations such as tail tracks.

Other authorities, in order to limit costs, elect to equip only the mainline with CBTC and to implement a stand-alone conventional signaling system for yards and depots. This mandates the use of human drivers to prepare for service even in a UTO system. It also introduces the need for a transition zone through which a train must travel to enter into CBTC operation from "dark" territory. Such a transition zone often incorporates functionality to verify that the train is fit for service. This arrangement may also provide a portion of the system that can protect non-CBTC-equipped MOW vehicles without heightened dependence on procedure.

Some authorities go still further, equipping only certain portions of the mainline, e.g. higher-density portions only, or areas perceived to be well-suited to

CBTC implementation. This approach can save equipment costs, but the added complexity of implementing zone-based CBTC, including potentially complex entry-exit functionality in the context of ongoing revenue service, has to be carefully managed: it can actually turn out to be more costly than implementing full line coverage, due to the associated implementation risk.

TWC Characteristics

Some TWC factors that should be considered when specifying and selecting the CBTC include the following:

- What data transfer capacity and latency requirements need to be met by the TWC? The amount of basic CBTC data capacity required for different systems can vary widely, older systems typically requiring the transfer of less data due to historical data link technology constraints.
- Is there a preference to use licensed or unlicensed frequency bands? Do local Authorities Having Jurisdiction impose explicit requirements in this area, or is there a choice to make?
- Is there a high risk of interference from the public domain that must be tolerated (e.g. a flood of potentially conflicting cellular communication at certain times of the year, as in Makkah, Saudi Arabia during the annual Hajj pilgrimage) that may represent a denial of service condition?
- Is there a high risk of malicious intrusion by "hackers," and to what extent should more sophisticated and costly defense mechanisms be considered?
- Is there opportunity to share other communication backbones in the system for certain CBTC communication links, TWC or otherwise? To what degree can critical and non-critical data be effectively segregated within the shared medium (noting that CBTC data must be granted priority over other data like CCTV image or VoIP data, due to its time-sensitivity and mission-criticality)?
- Is there a preference for current technology such as WiFi, or would older technology be an acceptable solution? Depending on locale, it may be appropriate to conduct a tradeoff analysis to answer this question, given the diverse associated factors, such as openness of vendor selection, end of life considerations, rapidity of obsolescence, mechanical robustness, impacts on train dynamic envelope and track maintenance.

Fallback Capabilities

With a proper Systems Engineering approach, the CBTC can usually be designed to be adequately reliable and fault-tolerant, such that incorporation of STC for fallback can be deemed unnecessary. The unattended CBTC system with the longest history in the world, the Vancouver SkyTrain, safely operates without STC: in the rare case of full CBTC failure, adherence to strict operating procedures protects trains operating in degraded mode, until the CBTC is restored. Monorail systems and Automated People Movers also commonly exclude STC from their configuration. A tradeoff study may need to be undertaken to decide the extent of fallback capabilities to be implemented, given the associated costs, benefits and risks.

Collaboration between the CBTC and the CBTC-ready Interlocking, including switchovers of control and ongoing interface during normal operation, is critical to reliable operation of a CBTC system with STC. If either the CBTC or STC system suppliers do not have experience integrating the two specific products being implemented (even if one supplier is supplying both of them), then it is important to identify and manage associated implementation risks throughout the upgrade.

Operationally, if it is decided to include STC in the system configuration, the following must be borne in mind: a STC system will most likely support a significantly lower train density than the CBTC. Therefore, when STC service commences in a fallback scenario, there is a strong likelihood that it will begin with trains closer together than its own interlocking rules would allow. It will be critical to design the CBTC-ready Interlocking to gracefully handle this scenario, and later on, to allow transition back into CBTC operation without widespread controller restarts or the like.

Inclusion of STC in a CBTC upgrade can appear a less risky operational choice, but it does introduce additional hardware that can fail, which can actually result in a lower availability and higher maintenance costs than CBTC alone, if not done carefully.

PLANNING THE CBTC UPGRADE

The public is highly dependent on the service provided by an operational mass transit system, so most transit authorities do not have the luxury of shutting down system operations for weeks or months at a time, in support of a "brownfield" upgrade. Even in the case of a "greenfield" implementation, where no pre-existing system exists, the logistics surrounding rolling stock manufacturing, land appropriation and the securing from Authorities Having Jurisdiction of authorizations to proceed can all render a "big-bang" implementation, where the entire fleet and line begin CBTC operation all at the same time, impractical if not impossible. The majority of CBTC upgrades involve staged implementations, the most complex being brownfield projects, so this portion of the paper will focus on these.

The overall sequencing of a CBTC upgrade will depend on the context of related contracts and supporting retrofits. A sample schedule is included in Figure 2. Some factors to consider include the following:

- Will the upgrade include supply of new rolling stock? How does the rolling stock delivery schedule correlate with the CBTC supply schedule? Should CBTC commissioning start with the new fleet, the old or both at once?
- To what extent and how will compatibility between the new CBTC system and existing systems be ensured? This is especially important in terms of the safety assurance of original equipment that is no longer supported by the supplier (one of the main reasons that Properties embark on an upgrade). Consider existing ATS, rolling stock and Interlocking systems to be retrofitted or replaced.
- Will the system include a geographical extension so that the project involves both greenfield and brownfield zones?
- Will it be feasible to implement “shadow-mode” testing, to find and correct data problems earlier?

Although extended shifts may occasionally be made available on weekends or holidays for particularly complex test activities, most installation and testing activities associated with a brownfield CBTC upgrade must be accomplished during non-revenue hours, so-called “engineering” or “maintenance” shifts, between say 2:00 am and 5:00 am. Effective planning during this period is essential to ensure efficient use of the precious time available. It must accommodate not only installation and test activities (so-called “screwdriver time”), but also setup and vehicle transfer activities, not to mention the sharing of portions of the system with ongoing preventive maintenance activities of the railroad. For this reason, it is important while planning the upgrade to maximize simulation and shadow-mode testing, and to mitigate the risk of schedule over-runs associated with shifts requiring precious site access, through the careful planning of cutover installation and test activities, including a strategy for the backing out of unsuccessful changes wherever possible. All staff, including those of Subcontractors, who will participate in site commissioning should be required to attend weekly site planning meetings.

In principle, installation and commissioning of much of the CBTC-specific infrastructure, and associated training of O&M staff, can be readily accomplished in parallel with ongoing revenue operations. The main exceptions relate to “cut-in” activities that require modifications to existing systems, such as the retrofit of Interlockings (to render them “CBTC-ready,” if they themselves are not to be replaced); upgrades associated with the central HMI; or introduction of new trackwork associated with the introduction of a new, connecting line or extension.

Once the CBTC requirements and design are complete, and the first articles of MACs and CCs have been produced and factory tested, installation and testing in the field can begin: both for carborne and wayside components.

Upgrading the Central Office Equipment

For a CBTC MB upgrade, it is likely that the ATS will be replaced, since a conventional signaling system subject to replacement is unlikely to be driven by a MB-compatible ATS. The central ATS upgrade can be a single event (if there are remote ATS workstations near the existing Interlockings, they may be subject to staged upgrade), however the replacement or upgrade of existing Interlockings happens in stages: one zone at a time.

If the existing Interlockings are being upgraded to support CBTC, then they can be designed to communicate with both the existing and new ATS, and it will be best to introduce the new ATS after all the Interlockings have been implemented. If not, it is typically more feasible to upgrade the ATS first, ensuring that the new ATS is compatible with the existing Interlockings, since the non-safety-critical software of the ATS is cheaper to design, construct and qualify than the safety-critical Interlocking software. This approach will provide operators with advance exposure to their new, CBTC-compatible interface, prior to commencement of actual CBTC operation, which will itself require a conceptual adjustment. Separating these two adjustments, HMI and CBTC, can lessen the impact on operations staff, but note that it will also spread out the adjustment period, which may or may not be desirable, depending on the nature of operation and the collective personality of the affected teams. There are many factors that may lead to selection of the alternate option, including availability of documentation and programmers able to work with the existing interface software. Managing this interface is essential to effective project risk management.

Installation of the main HMI, ATS servers, backbone switches etc. in the Central Office can typically proceed with a minimum of disruption, up to the point of replacement of hardware in the Control Room (i.e. operator workstations: keyboards, monitors, pointing devices). At this point, depending on the scope of the Control Room upgrade, it may become necessary to relocate Control Room operations staff, to implement the upgrade quickly and efficiently. Some options for relocation may be to a new or existing backup Control Room, or to a simulation room used for Operations training, if such is available. Some factors to consider in the Control room upgrade are consistency of user screens and monitors with existing layouts, levels of sound and heat generated by new hardware, and other human factors.

Upgrading or Replacing Station Room Equipment

If the existing Interlockings are nearing End of Life, they should be replaced with new, CBTC-compatible Interlockings. If not, they will need to be upgraded to support CBTC-compatibility. In either case, it may make sense to replace the Interlockings with CBTC ZCs that incorporate Interlocking and MAC functionality together in the same controller, with a minimum of hardware. This consideration should be the topic of a trade-off analysis.

If independent Interlockings are to be retained, then their control boundaries must be coordinated with those of the MACs, to both facilitate train transfer among zones and allow coordination of testing. Full compatibility must be ensured between the new or upgraded Interlockings and the CBTC. This requires some knowledge of both the Interlocking and CBTC functionality from the start, and can result in a coordination challenge similar to that faced when purchasing rolling stock in advance of other, interfacing systems. The associated complexity is amplified if different suppliers are selected for Interlockings vs. CBTC. These options may optionally be rolled into the scope of the CBTC upgrade, as CBTC suppliers often have some experience with Interlocking interfaces. In any case, MACs, like Interlockings, are installed and tested one zone at a time, unless schedule recovery calls for parallel activity in multiple guideway locations, which increases project complexity.

If integrated Interlockings are to be introduced, then there will be a period of time during which a part of the operational system will be controlled by the CBTC and the rest will be controlled by the existing Interlockings. It is advisable to minimize the number of portals through which trains may pass to transfer between the old and new territories, to keep the operations strategy simple, especially since the condition occurs during a transition phase of the project.

Upgrading the Trackside Equipment

Most trackside equipment will have to be installed in locations that are required to support ongoing revenue service throughout the upgrade. In this case, installation must take place under work or occupancy permits, and normally during the non-revenue window.

Trackside equipment unique to the CBTC system, such as transponder tags/balises and radio transceivers and associated cabling, can be installed relatively quickly, where it does not detract from the function of the existing signaling system.

If geographic expansion of the line is included in the project, then installation and commissioning of the cut-in points, especially if the introduction or relocation of turnouts is involved, will require an extended period of down-time, every detail of which must be meticulously planned, avoiding high-demand periods in the calendar, and rigorously executed, to minimize service impact.

Upgrading the Rolling Stock

For existing rolling stock, three cases are considered: where space can be allocated on cars to allow the installation of new CBTC equipment without the decommissioning of existing controllers that are required to support ongoing revenue service, both with and without cutover capability; and where no such space is available.

- Where space is available: cars can be taken out of service one by one, retrofitted with the additional CBTC hardware and returned to service, independent of the deployment of wayside CBTC components. This equipment would be configured initially to function in a read-only configuration, in support of “shadow mode” testing.
- For consists for which cutover capability is also possible, they may be configured to temporarily allow CBTC control, to support type and integration testing, then returned to shadow-mode testing configuration. The remainder of the fleet would require subsequent retrofit to convert from shadow-mode to full-CBTC configuration. Even those having cutover boxes should be consolidated when commissioning is complete, to eliminate superfluous hardware that can impact reliability.
- Where no space is available, decommissioning of existing carborne signaling equipment will be necessary to make space for the carborne CBTC equipment. In this case, the CBTC retrofit of the fleet should wait until later in the program, apart from a dedicated test train or two, until the wayside CBTC components have been fully tested and verified to be fit for revenue service.

For new rolling stock, CCs will typically be shipped to the vehicle manufacturer’s premises, and installed prior to vehicle shipment to the transit property. The vehicle production schedule and the level of sophistication of the vehicle manufacturer’s facilities will determine the extent to which vehicles can be pre-shipment tested. At a minimum, static “post-installation checkout” tests are typically undertaken, including wiring ring-outs, etc., but with appropriate test facilities, dynamic testing and burn-in may also be possible pre-shipment.

Site testing of rolling stock for CBTC functionality (primarily ATP and ATO) can be subdivided into tests that must or need not be completed to support shadow-mode and later system-wide testing. The Automatic Speed Control component of the ATO function, for example, is highly dependent on the correct functioning of all other carborne systems, and is therefore likely not be complete until later than the start of zone-based CBTC testing, whereas verification of the CCs' capability to communicate with MACs is essential from the outset.

Training

It is important to deliver training to the O&M staff at the right point in time: not too early, such that the concepts and material may be forgotten, nor too late, such that staff are expected to use something they have not yet been trained to use.

The training of operations and maintenance staff can begin once the designs are mature (i.e. first articles produced and tested, and major design issues rectified) and should be complete prior to the start of system-wide testing, relocation to the main Control Room, whichever comes first. It can be beneficial for operators to be given high-level CBTC training prior to initial exposure to CBTC functionality during zone testing, followed by more comprehensive functionality training throughout the zone testing period and prior to the start of system-wide testing and demonstration of system operation.

A key benefit of CBTC is the typically sophisticated simulation capabilities that are available to be included in the system configuration. These can be used for off-line staff training and certification, and some components may also support backup Control Centre facilities.

Go-Live Planning

A scheduled Demonstration of System Operation (DSO) prior to carrying passengers in revenue service may be advisable, with or without passengers, with discounted trips, for a number of reasons:

1. It allows the Project Company (not necessarily the same as the Operating Company) to ensure the supplier has met its obligations prior to granting final acceptance.
2. It gives control operators the opportunity to experience the new functionality in a lower–risk environment than normal revenue service

The DSO period may apply to all CBTC-equipped trains or a subset of trains, depending on the fleet commissioning schedule. If a revenue (i.e. carrying passengers) DSO is planned, it may advisable to implement trip discounts, or to plan to take interim delay compensation measures, in recognition of the potential for delays. If non-revenue DSO is planned, the potential associated perception, political issues and media exposure will have to be carefully managed, when empty trains are observed traveling at high frequency for an extended time period, which in the minds of some may appear wasteful.

Safety Planning

The safe operation of the railroad has naturally to be assured throughout the upgrade, from the moment the first new equipment is installed until the issuance of the Final Acceptance Certificate when the upgrade is complete. There will be periods during which interim system configurations are in place, which are similar but not identical to either the original or final configurations. These interim configurations may include temporary equipment such as cutover boxes to transfer control of portions of the railroad between new and old systems. Such equipment needs to be analyzed in the context of railroad operation, to ensure that acceptable levels of safety are maintained for every step of the upgrade. Most safety incidents are encountered during times of uncommon operation, of which a signaling upgrade is a significant one, so it will be important to exercise heightened safety sensitivity during this period, perhaps conducting safety refresher training for operations and maintenance staff and contractors just prior to commencement of the commissioning phase of the upgrade.

The sequencing of system upgrades is important. For example, if the Tunnel Ventilation System (TVS) can support the current minimum train spacing based on existing block lengths, but needs to be upgraded to handle increased train density, then it may be necessary to upgrade TVS first, then traction power sections, then the signaling system. Driverless operation is likely not to be authorized prior to PEDS or GIDS deployment, so this needs to be reflected in the program schedule.

CONCLUSIONS

The decision to implement a CBTC upgrade depends on various technical, political and human factors. The success of a CBTC upgrade will depend on following a proper systems engineering approach, starting with needs definition, continuing with comprehensive tradeoff analyses and applying rigorous project and risk management throughout. CBTC has the potential to significantly increase the performance and reduce the operating and maintenance costs of the railroad, and if properly implemented, promises to bring many years of benefits to the Railroad and the riding public.

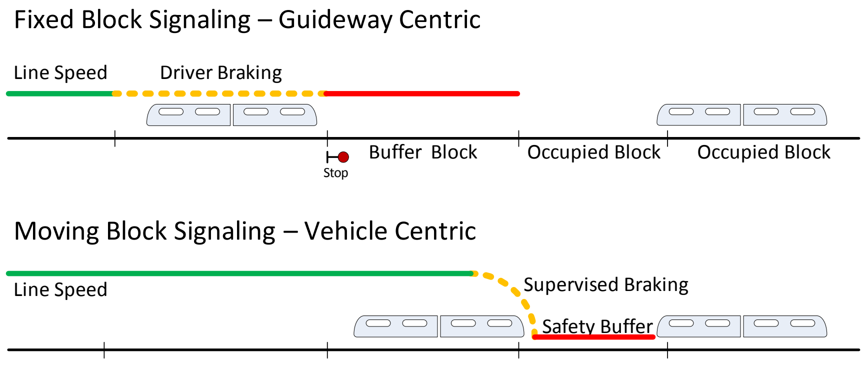

Figure 1: Fixed Block vs. Moving Block – Concept

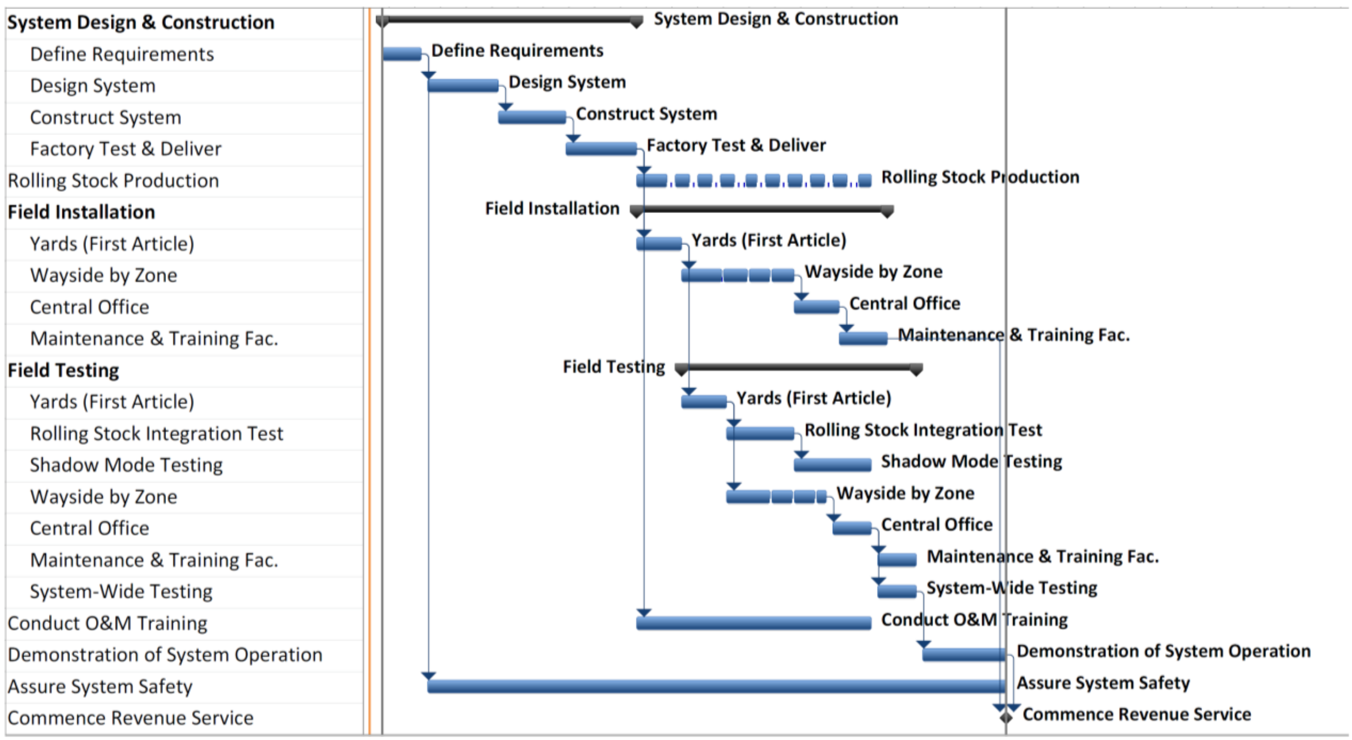

Figure 2: Example Level 1 Schedule for CBTC Upgrade

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