CBTC Train Operation Over Failed Track Circuits

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ABSTRACT

In recent years, many rapid mass transit agencies have chosen Communications-Based Train Control (CBTC) technology to renew their signaling system or to equip a new line. CBTC technology is a type of Automatic Train Control (ATC) that allows transit agencies to increase nominal throughput and to improve safety. The main functions of CBTC are described in [1.] and [2.]

CBTC technology can operate without fixed wayside track detectors such as track circuits. However, track circuit equipment continues to be implemented on the tracks and in the equipment rooms. For authorities under the Federal Railroad Administration, current regulations require use of track circuit but the main functional reason is to have a backup system in case of CBTC failure. Most transit agencies decide to include track circuit occupied and vacant status into the CBTC system in order to enhance safety. The additional safety feature brings a new challenge: how to detect and to manage CBTC operation when track circuit failure occurs.

This paper discusses the challenges of maintaining safe and efficient train operation over failed track circuits. The consequences of the track circuit failures on the signaling system are not addressed in this paper. They are described in [3.]. First, the different type of track circuit failures and how the CBTC system detects them are introduced. Then the paper discusses possible restrictions on CBTC train operation and the associated enforcement methods. Finally, the different methods to return to normal CBTC operation, after the failure has been fixed, are presented. Transit agencies' different approaches to maintain safe operation, as well as possible future options to manage track circuits failures with a CBTC system, are explained.

List of Acronyms

ARB	Always Reporting Block
ATC	Automatic Train Control
ATO	Automatic Train Operation
ATS	Automatic Train Supervision
CBTC	Communication Based Train Control
CC	Carborne Controller
MAL	Movement Authority Limit
NRB	Never Reporting Block
OCC	Operation Control Center
SIL	Safety Integrity Level
TOD	Train Operator Display
ZC	Zone Controller

DEFINITIONS

Always Reporting Block

The most common track circuit failure is when the track circuit is always reported as occupied to the wayside equipment. This type of failure is named Always Reporting Block (ARB). Whether a train is on the track circuit or not, the track circuit is seen as occupied by the wayside signaling system. The possible causes for this type of failure are numerous. To mention just a few: broken rail, tuning box in need of maintenance, failure of the track circuit board, failure of a track circuit repeater relay or a connection loose in the wiring. ARB results in difficulties for train operation but it is considered as a failure of the equipment on the safe side.

Never Reporting Block

The second type of track circuit failure is when the track circuit is always reported as vacant to the wayside equipment. It is never reported as occupied even if a train occupies the track circuit. This failure is named Never Reporting Block (NRB). There are several possible causes, but the most common origin is a human error during maintenance or upgrade operation. Other possible causes can be a design flaw, rusty running rails, and poor shunting of vehicles. NRB can lead to collision at normal operating speed, therefore it is an unsafe failure. One example is described in [4.].

CBTC system and subsystems

CBTC system is composed of several major subsystems:

- The on-board controller, also called Carborne Controller (CC), is located on-board the train. The CC is responsible for determining the train speed, train location and also to enforce the speed limit and Movement Authority Limit (MAL). The software contained in the CC performs vital functions. In Europe, the vital functions are developed with the highest software Safety Integrity Level (SIL) according to [5.].

- The Zone Controllers (ZC) are located in the technical rooms. There are several ZCs per project to provide coverage for a line. They exchange information with the on-board controller in their zone via a radio system. The software contained in the ZC performs vital functions. In Europe, the vital functions are developed with the highest software SIL according to [5.]. The ZC is responsible for computing MAL and to forward it to the trains in its zone. It also detects track circuit failures based on comparisons of the CC location report and on track circuit status provided by the signaling system.

- The Automatic Train Supervision (ATS) system, which regulates trains, is the interface with the operators located at the Operation Control Center (OCC). The software contained in the ATS performs non-vital functions and therefore it is not developed with the highest software SIL according to [5.].

CBTC Control Mode Operation

This paper uses the term CBTC control mode to refer to the operating train modes under CBTC protection. In CBTC control mode, the on-board controller triggers an emergency brake when it detects a possible unsafe situation such as excessive speed. CBTC control mode can be in Automatic Train Operation (ATO) mode or in manual driving mode. CBTC control mode is also referred as a mode with CBTC supervision, a mode under CBTC protection or an Automatic Train Protection (ATP) control mode.

METHODS TO DETECT ARB

The ZC is responsible to detect ARB based on the tracking of both CBTC and non CBTC trains and also based on the track circuit occupancy status received from the signaling system. The ZC compares which track circuit should report occupied based on its train tracking and which ones actually report occupied. The ZC determines there is an ARB when it detects that track circuit occupancy is not due to a train occupying the track circuit.

Sudden occupation of a track circuit

When a track circuit which is not at the border of the CBTC territory suddenly reports occupied while other adjacent track circuits remain reported vacant, an ARB is detected as shown in Figure 1.

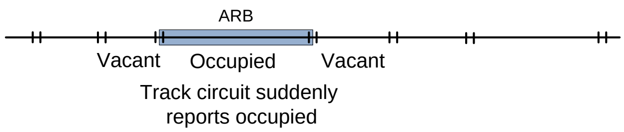

Figure 1 ARB detection using sudden occupation of track circuit

For track circuits at the limit of the ZC territories, a message exchanged with the adjacent ZC is used to determine track circuit failure. The ZCs exchange the status of the track circuits at their limit of territory. Note that the track circuits at the border of the CBTC territory cannot be detected as ARB. When a track circuit at the CBTC border becomes occupied, the ZC considers a train is entering the CBTC territory and starts tracking a train on this track circuit, even if the train is not equipped with CBTC.

Using train location report

The CC determines the CBTC train location and location error and then sends the information to the ZC for its tracking function. When a CBTC train passes over a track circuit, the ZC expects the track circuit to be occupied and then to report vacant once the train frees that track circuit. In addition to the location report provided by the CC, the ZC also uses the train overhang (distance between the train extremity and the first axle shunting the running rails), the different computer cycles, the communication network delays, and the time delay for track circuit equipment to change status in order to determine exactly which track circuit should be reporting as occupied. If the track circuit continues to report occupied after the train location does not span the track circuit anymore, the ZC detects an ARB. In most CBTC systems, if the CC does not report a loss of train integrity, then the ZC is able determine that no train is present on the ARB track circuit.

Using an ATS operator command

One method for the ZC to consider a track circuit ARB is to have the information provided by the ATS operator. Although rare, some projects include a command from the ATS operator to have the ZC consider that a track circuit is failed. In projects using this method, the ATS message indicates a track circuit failure and does not distinguish between ARB and NRB. The occupancy or vacant status of the track circuit is not taken into account. The ATS operator can also indicate to the ZC that the track circuit has been repaired.

METHODS TO DETECT AN NRB

Using train location report

Using CBTC train locations and associated location errors, the ZC is able to determine which track circuits should be reporting occupied. The ZC determines a track circuit is NRB when it is reported vacant by the signaling system while the ZC determines that at least one train is shunting the track circuit and therefore the track circuit should report occupied. This principle is shown in Figure 2.

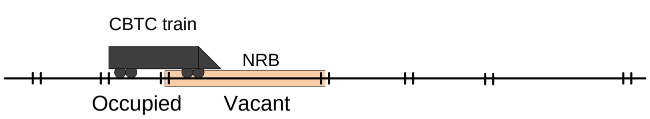

Figure 2 NRB detection using train location report

Using non CBTC train tracking

In some projects, the ZC detects NRB using tracking of non CBTC trains. When a non CBTC train suddenly cannot be located on any track circuit, the ZC considers the last occupied and the adjacent track circuits as NRB. At minimum, three track circuits are tagged NRB as shown in Figure 3. Note that the track circuits at the boundary of the CBTC territory cannot be detected NRB using this method.

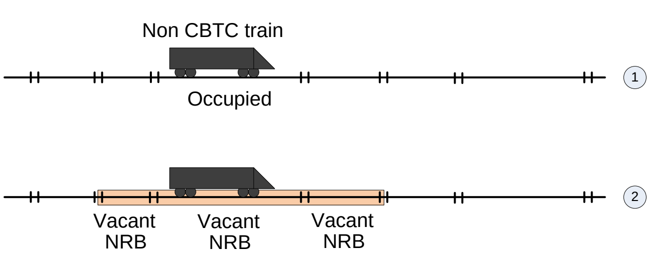

Figure 3 NRB detection using tracking of non CBTC train

DETERMINING TRAIN PRESENCE OVER A FAILED TRACK CIRCUIT

When a non CBTC train passes over a failed block, ARB or NRB, the ZC assumes that one or several cars of the train remained on the failed track circuit. Indeed, the ZC cannot determine that all cars of the train left the track circuit. This safety principle is applied despite a sequence of track circuit occupancy indicating that some cars of the non CBTC train vacated the area.

If the ZC cannot determine that the failed track circuit is vacant, CBTC trains maintains a buffer track circuit between their front and the failed block. In order for the ZC to determine that no car is left on the failed track circuit, a CBTC train must run through the entire block without CBTC protection. The CBTC train controlled manually by the Train Engineer reports its location when running over the block. Since a CBTC train running in manual without CBTC protection succeeded to pass over the zone, then the CBTC determine that there is no car left on the block by the preceding train. The ZC determines that no car was left on the block at the time the distance between the front of the CBTC train and the beginning of the next vacant track circuit becomes smaller than the minimum length train in the system. Some advanced system also use algorithms taking into account the train speed. This method is called “sweeping”. The sweeping method uses the communication between CC and ZC and therefore it does not work with non CBTC trains.

CONSEQUENCES ON CBTC TRAIN OPERATION

CBTC train operation over an ARB

Consider the case when an ARB is detected by the ZC and the ZC determined there is no train on the ARB. There are two different methods of operating CBTC trains over an ARB.

The first method is to forbid CBTC control mode operation over ARB, the Train Engineer drives manually without CBTC protection. When driving manually with no CBTC protection, the maximum train speed is limited. The enforcement of the constant maximum speed can be done by the rolling stock or by the CBTC depending on the project. One of the reasons to choose this conservative option is to facilitate safety certification for revenue service. Also some transit agencies want the Train Engineer to drive manually the train in this situation, so that he/she can entirely focus on line of sight and not use any MAL shown on the Train Operator Display (TOD).

Another reason to forbid CBTC control mode operation on ARB could be a limitation of the CBTC used for the project which does not make the distinction between ARB and NRB. As discussed later, CBTC operation on NRB is usually forbidden.

Second method for operating over an ARB is to authorize CBTC control mode operation on the failed block. Depending on the CBTC system and on the transit agency, there are various ways to run in CBTC control mode operation over an ARB. In projects where ATO is possible, when a Train Engineer is on board the train, transit agencies prefer to have the Train Engineer change to manual operation with CBTC protection. The ATO stops the train at the failed track circuit limit and waits for the Train Engineer to change the CBTC control mode to manual mode with CBTC protection. The manual mode with CBTC protection includes a constant speed restriction over the entire block. Note that for driverless projects, some transit agencies authorize ATO on an ARB at normal or at reduced speed.

Another difference between CBTC projects is the need for an ATS operator confirmation before CBTC trains can operate on the ARB. Even when the ZC determines that no train is present on the ARB, some projects require that the ATS operator sends a command to the ZC before allowing CBTC control mode operation over the area. This command provides what is called a “Restricted Authority”. CBTC operation is only possible under certain restrictions. When the command is received, it can be valid for several CBTC trains. It is valid until a cancellation command is sent, or the block is no longer ARB, or a non CBTC train runs over the block. As stated earlier, when a non CBTC train runs over the ARB block, the ZC cannot determined if the non CBTC train did not leave a car on the failed block, therefore, as a safety precaution the ZC cancels the authorization to travel in CBTC control mode over the ARB.

CBTC train operation over an NRB

To the author’s knowledge, there is no CBTC project using track circuit information which authorizes CBTC control mode operation over a detected NRB. To run over an NRB, a Train Engineer must be on board the train and drive manually based on line of sight, without CBTC protection. The only limitation enforced by the CBTC is a slow constant maximum speed in manual mode.

NRB is rare but it can lead to potentially unsafe situations in conventional signaling systems. This partially explains the conservative choice to rely on the train operators and not permit any automated operation. Usually automated train control is used to avoid human errors such as overspeed, but in case of NRB, humans are used to handle a signaling system failure.

In the future, CBTC control mode operation might be possible under severe conditions similar to the conditions used for a train to pass over ARB. The ZC would first need to determine that there is no train on the NRB using the “sweeping” method. After the ZC determines there is no train on the NRB, operation at normal or at low speed would be permissible. An ATS operator command could be included to authorize CBTC operation over the NRB and to cancel the authorization when needed. This method would be used to handle train operation over NRB during peak time and allow postponing the maintenance to off peak hours.

CONSEQUENCES ON TRAIN TRACKING

Train Tracking over an ARB

ZC tracking

The ZC tracks CBTC trains using the reported location and location error without considering the track circuit status. ZC tracking of CBTC trains on ARB is therefore not degraded.

The tracking of non CBTC trains, which do not report their location, is affected by an ARB. When a non CBTC train occupies the track circuit immediately in approach to the ARB, the ZC determines that the train can be on the track circuit occupied by the train and also on the ARB. After the train has vacated the ARB and the track circuit immediately after the ARB, the ZC continues to track the train normally. However, it assumes that there is a new potential non CBTC train on the ARB. This block has to be swept by a CBTC train running in manual mode without CBTC protection before ZC can allow CBTC operation on the failed track circuit.

ATS tracking

The ZC provides to the ATS both the ARB and NRB status of every track circuit. Similar to the ZC, the ATS system tracks the CBTC train using the reported location and location error, without taking into account the track circuit status. Therefore the tracking of CBTC trains on ARB is not degraded.

The tracking of non CBTC trains can be degraded by an ARB. In the case where the ZC has detected the ARB and provided the information to the ATS, the ATS is not able to determine if a train is on the ARB or on a track circuit adjacent to the ARB. The tracking accuracy is degraded when the train passes over the failed block and the adjacent blocks but ATS resumes normal tracking after the train vacates the area. In the case where the ZC has not yet detected the ARB and provided the information to the ATS, the ATS assumes that the non CBTC train remains on the ARB. The ATS then determines all other track circuits occupied by the non CBTC train as occupied by a new unknown train. To avoid this situation and the associated alarms, an ATS operator action is required.

Train Tracking over an NRB

ZC tracking

The ZC tracks CBTC trains using the reported location and location error. Since the ZC does not rely on track circuit status, the tracking of CBTC trains on NRB is not degraded.

The tracking of non CBTC trains is based on the track circuit status and therefore can be degraded by an NRB. On some project, when a non CBTC train passes over an NRB, the ZC loses the location of the non CBTC train and raises an alarm. When the non CBTC train starts occupying the next track circuit which is not NRB, the ZC detects an ARB on the track circuit occupied by the non CBTC train. All the track circuits occupied by the non CBTC train are then detected ARB until the train reaches the territory limit of another ZC. On other projects, the design is improved to avoid this issue, but it adds complexity to the system for managing the rare scenario of a non CBTC train passing over an NRB.

ATS tracking

Similar to the ZC, the ATS system tracks the CBTC train using the reported location and location error, without taking into account the track circuit status. Therefore ATS tracking of CBTC trains on NRB is not degraded.

ATS tracking of non CBTC trains can be degraded by an NRB. In the case where the ZC has detected the NRB and provided the information to the ATS, the ATS tracking is degraded and ATS considers the NRB as occupied in its tracking function. The ATS is not able to indicate if a train is on the NRB or on a track circuit adjacent to the NRB. If the ZC has not yet detected the NRB and provided the information to the ATS, the ATS loses the location of the non CBTC train when it enters the NRB and exits the last track circuit which reports occupied. ATS raises an alarm to indicate that the location of the train is lost.

RESTRICTIONS ENFORCEMENT ON A FAILED TRACK CIRCUIT

CBTC technology is capable of different types of restriction enforcement over a specific zone. The restrictions to be enforced are a slow speed zone and/or control mode restriction (manual with or without CBTC protection). In manual without CBTC protection, the speed enforcement can be done by the CBTC or by the rolling stock depending on the project.

A restriction over a zone can be enforced in two different manners: on entire train length or based on train front only. A common practice is to use the same type of enforcement for both ARB and NRB failures. Depending on the project, the enforcement of track circuit failure restriction by CBTC trains is on entire train length or based on train front only. The enforcement on entire train length is more conservative and is the method chosen by the majority of transit agencies.

Enforcement on entire train length

Enforcement on entire train length is the term used when the CC enforces the restriction as long as any part of the train is located on the restricted zone. This type of enforcement is possible because the CC determines its location and associated location error. For instance, this method is used to enforce civil speed limit. Figure 4 shows how a train using this type enforcement passes over a restricted zone.

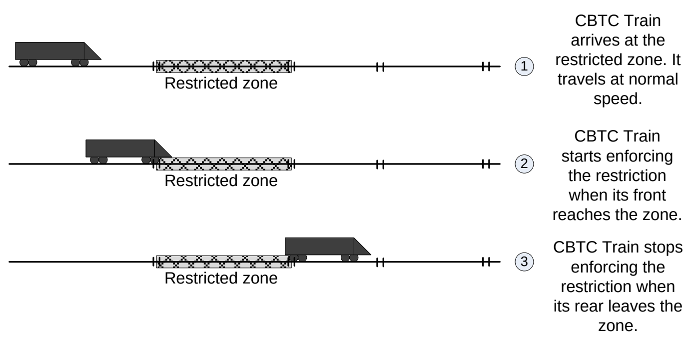

Figure 4 Enforcement on entire train length

Enforcement based on train front

Enforcement based on train front is the term used when the CC enforces the restriction only when the front of the train is located in the restricted zone. The difference with the enforcement on entire train length is when the train exits the area. As soon as the train front exits the zone, the restriction is not enforced anymore as shown in step 3 of Figure 5. This method allows the train to resume normal operation earlier than the method of enforcement on entire train length.

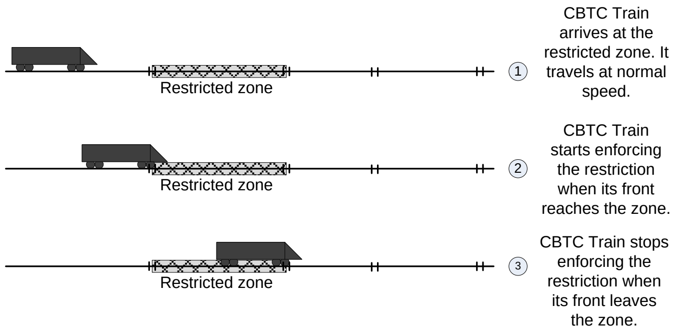

Figure 5 Enforcement based on train front only

Type of brake to apply

In case the restriction associated with ARB or NRB starts to apply while a CBTC train is running over the block, the CC initiates application of the train braking system. This situation can happen when an NRB is detected or when the ATS operator cancels the authorization for the CBTC train to run over the ARB in control mode under CBTC protection. The type of braking depends on the project. Some CBTC projects have the train apply emergency braking while other recent projects use full service brake. The full service brake is monitored and an emergency brake is applied in case the full service brake is not reducing the speed of the train fast enough. Full service brake application is usually preferred because it is less violent for passengers and less demanding for the rolling stock. Also, in case of ARB and when CBTC control mode operation is allowed, it may give the opportunity for the train to comply with the restriction without stopping.

INFORMATION ON THE TRAIN OPERATOR DISPLAY

Train cabs are equipped with a Train Operator Display (TOD) to provide information from the CBTC system to the Train Engineer. The main information is the current speed of the train, the maximum speed to enforce the CBTC protection, and the distance to the movement authority limit and the type associated with this limit. The type of the limit can be a train or an interlocking signal at stop for instance. In manual mode without CBTC protection, the cab usually only displays limited information such as the current train speed and a fixed pre-determined maximum authorized speed corresponding to the manual mode without CBTC protection.

For projects that allow CBTC train operation in manual mode with CBTC protection over a failed track circuit, the movement authority limit and the type associated with the limit can be overridden by the track circuit failure information. When the train is enforcing the restriction, the transit agency may decide to have the MAL displaying failed track circuit with a distance to the limit equal to zero instead of the actual MAL being taking into consideration by the CC.

METHODS TO RESUME NORMAL OPERATION

After an ARB has been fixed

The ZC is responsible to detect when the ARB conditions are not applicable anymore. The ZC detects that the ARB can be removed when the block reports vacant. After the block reports vacant, there are different methods to resume normal CBTC operation over the area. On some projects, only the ZC manages ARB and therefore as soon as the ARB reports vacant, the ARB status is removed. Normal CBTC operation over the area resumes immediately.

On other projects, when the ARB reports vacant, the ZC detects that the ARB status can be removed but keeps a memory of the ARB status. The ARB restrictions on CBTC train operation are maintained. The ATS operator is required to send a command to the ZC to confirm that the memory of ARB status should be reset. Only after the ZC receives and accepts the ARB memory reset command, the system can return to normal CBTC operation over the area. This approach is recommended in [6.] and is described in the diagram of Figure 6.

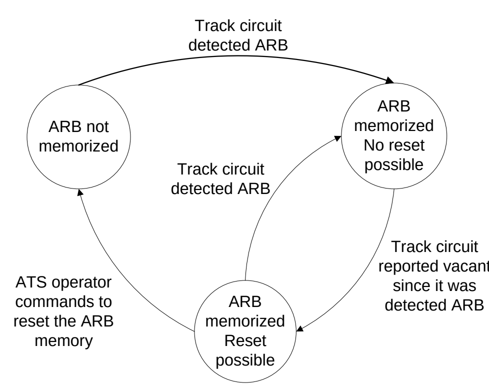

Figure 6 Example of recovering from ARB

After an NRB has been fixed

The ZC is responsible to detect when the NRB conditions are not applicable anymore. The ZC detects that the NRB can be removed when the track circuit is reported as occupied.

On some projects, only the ZC manages NRB and therefore as soon as the failed block reports occupancy, the NRB status is removed. Normal CBTC operation over the area resumes immediately. On other projects, when the NRB reports occupancy, the ZC detects that the NRB status can be removed but keeps a memory of the NRB status. Some projects require that track circuit occupancy be done using CBTC trains running over the track circuit. The ATS operator then is required to send a command to the ZC in order to indicate that memory of NRB status should be reset.

Some CBTC projects have introduced another limitation for the ZC to accept the NRB memory reset command from the ATS. The command must be sent while the track circuit is reported as occupied.

CONCLUSION

The method to maintain CBTC operation over track circuit failures is different from one project to another. It depends on the transit agency choices and on the CBTC product flexibility.

The only common approach between CBTC projects is to forbid CBTC operation on NRB. Usually, automated train control is used to avoid human errors such as overspeed, but in case of NRB, humans are used to handle a signaling system failure.

Both ARB and NRB failures concern track circuit equipment, however, they are two very different failures. CBTC projects have the ability to manage the failures as two separate challenges with distinct solutions.

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