JOINTLESS TRACK CIRCUITS FOR BROKEN RAIL DETECTION WITH STAND-ALONE PTC AND CBTC SYSTEMS

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ABSTRACT

A novel approach for implementing jointless track circuits is presented. Positive Train Control (PTC) and Communications Based Train Control (CBTC) systems have been widely deployed by railroads and rail transit in recent years. Many of these systems do not require track circuits, so broken rail protection is no longer an inherent part of their functionality. However, low cost specialized track circuits could close this functionality gap.

The proposed broken rail detection system is not intended as a replacement for a conventional signaling system and particularly not as a substitute for the vital safety logic that is currently provided by such a system. However, where PTC or CBTC systems without broken rail detection capability are installed in lieu of conventional signaling, the proposed approach can extend the PTC or CBTC capabilities.

INTRODUCTION

Positive Train Control (PTC)[1] and Communications Based Train Control (CBTC)[2] systems have been widely deployed by railroads and in rail transit in recent years. Stand-alone versions of these systems utilize more accurate train positioning data than track circuits could ever provide. But if track circuits are eliminated, so is ***broken rail protection.*** However, low cost specialized track circuit designs could provide this broken rail functionality without overtly duplicating the superior train positioning that modern PTC and CBTC systems provide.

This paper proposes a novel approach for using jointless AC and DC track circuits to develop a low-cost broken rail detection system. It presents a Concept of Operations and a mathematical framework for electrically modeling how such circuits might be expected to behave in practice. As will be explained, the new jointless track circuit design is often able to effectively detect shunts as well.

The proposed broken rail detection system is not intended as a replacement for the vital safety logic of a conventional signaling system. If safety vitality is not going to be provided by a signaling system, then it must be

[1] ***Positive Train Control (PTC)*** describes technologies that are designed to automatically stop a train before certain accidents caused by human error occur. For example, if a train operator fails to begin stopping before a stop signal or slowing down for a speed-restriction, PTC would apply the brakes automatically. [1]

[2] ***Communications-based Train Control (CBTC)*** systems offer flexible degrees of automation, from enforcing control over dangerous operations acted by the driver, to complete replacement of the driver role with an automatic pilot. [2]

provided by the PTC or CBTC system. ***Stand-alone PTC*** and ***CBTC*** systems[3] utilize direct communications with trains, can operate independently of track circuits and do not need a conventional signaling system. Instead of solely relying on track circuits for determining train location, stand-alone systems use various combinations of GNSS (Global Navigation Satellite System), wayside radio beacons, transponders in the track, inertial navigation, and dead reckoning (tachometers) for determining train location:

- A fusion algorithm in a computer onboard each train constantly monitors and integrates train positioning data within an accuracy of a few ***feet***, whereas track circuits can usually only resolve train locations within an accuracy of a few ***thousand feet***.
- Trains periodically share their locations with a wayside or central office PTC or CBTC server, usually via data radio, which manages movement authorities for maintaining safety.
- The PTC or CBTC server also integrates data from other sources, including track maintenance work authorities, grade crossing protective devices and track circuits.
- The PTC or CBTC server issues movement authorities to trains intended not only to guarantee safety but also to optimize the efficiency of the operation.

Historical Evolution of Track Circuits and Signal Systems

A track circuit works by applying an electrical current to the rails at one end of a track segment and detecting the current at the other end. A current received at the far end of a block is an indication that the track is safe. A shunt resulting from a track occupancy results in a ***short circuit,*** which ***reduces*** the current flowing through a detector at the far end of the track circuit. A broken rail results in an ***open circuit*** which ***eliminates*** current flow completely.

An open circuit is always going to be easier to detect than a shunt. The presence of even a minimum detectable level of current is enough to establish that the circuit is complete[4]. Additionally:

- The use of track circuits for broken rail detection does not depend on shunt capability, so this use is not affected by rusty rail or other kinds of intermittent contact problems that significantly affect the use of track circuits for detecting trains.
- Modern fail-safe approaches to protection of hand-thrown switches in track circuited territory rely on opening the track circuit rather than shunting it,[5] so an open switch is seen the same as a broken rail. Therefore, any track circuit that can detect broken rails can also detect a switch out of alignment.[6]

In many countries, track circuits have provided the foundation upon which railway signaling systems have been built. This led to the evolution of at least four distinct generations of signaling technology:

Generation 1: Early track circuiting concepts were very simple, requiring no more than a battery, a few resistors, and a relay. But while track circuits were simple, signal system implementation was complex. Multi-wired pole lines were needed for conveying occupancy and command and control data up and down the line, and complex

[3] Examples of CBTC systems include Thales' SelTrac and Alstom's Urbalis. PTC systems in the United States that could be capable of independent operations are Wabtec's I-ETMS and Alstom's ITCS. But while I-ETMS is approved by the FRA for independent operations, it lacks vital certification. While ITCS has vital certification and is operating independently in other countries, it has not yet been approved by the FRA for independent operations in the United States.

[4] Conventional track circuits have treated a shunt and open circuit condition the same since they only monitor current at the receiving end of the track circuit. Proposed "Next Generation" track circuits would monitor both voltage and amperage at both the sending and receiving end of a track circuit, so they could distinguish the difference between a broken rail and a shunt. "Single Ended Next Generation" track circuits have been proposed that monitor both voltage and amperage only at the transmission end and do not need a receiver at the far end of the block. However, "Next Generation" track circuits as currently proposed are primarily designed for detecting shunts just as traditional track circuits are. Such track circuits would offer performance enhancements within the traditional track circuiting paradigm but are not the focus of this paper.

[5] US 49 CFR § 236.60 prohibits using shunting for switch point protection and requires opening the track circuit, saying that a "*Switch shunting circuit shall not be hereafter installed, except where tract or control circuit is opened by the circuit controller.*" [4]

[6] By avoiding the requirement to install radio-based switch monitors on infrequently used switches or industrial sidings, this can result in significant cost savings in PTC implementations where protection of hand-thrown switch points is required.

relay-based logic was needed for determining signal aspects.

Generation 2: Coded track circuits, implemented as early as the 1920's by the Pennsylvania Railroad [5], ingeniously transmit data through the rails, reducing the need for pole lines. In a coded track circuit, signal logic is embedded into the track circuit controllers. Based on code rates in adjacent blocks, the hardware can determine what code should be sent farther down the line. Track circuit controllers became more sophisticated, complicated and expensive as a result, but the higher cost was offset by eliminating the need for pole lines.[7]

Generation 3: A third generation of signaling equipment, in use since the 1980's, introduced Solid State Interlocking controllers to replace electromechanical signal and interlocking logic [6]. The new solid-state devices were programmed to directly replicate relay-based signal logic and did not fundamentally change how signaling systems worked.[8] The third generation of signaling technology still did not anticipate the widespread deployment of high-speed electronic computer networks.

Generation 4: In the 21st century PTC and CBTC systems using high speed data networks became the fourth generation of signaling technology. These work on a fundamentally different principle than the previous generations. These fourth-generation systems rely on telecommunications and software for providing safety critical functionality. Trains directly report their own locations to computer servers, where the PTC or CBTC safety logic integrates all available information to determine if a proposed train movement is safe and imposes restrictions as appropriate. This is a fundamental change from third generation systems, which still distribute safety logic to the field, rely on track circuits for train positioning, and make safety decisions based only on a very limited amount of locally available data.

A clear focus of the implementation of both PTC and CBTC systems in North America has been on development of two-way data communications between trains, wayside and the central office.[9] For example, fiber optics have been installed along rail rights of way for supporting CTC (switch and signal control) functions as well as PTC communication requirements. Leased landline, ATCS data radio or public cellular data networks and satellite communications may alternatively be used for avoiding the high cost of a dedicated private communications network. Telecommunications capabilities already exist along many railroad rights of way and are used for many communications including PTC or CBTC-related and operational control functions. However, the challenges of cost effectively designing, and implementing complex safety critical systems have led to many PTC and some CBTC systems being implemented only as an "overlay" to second and third generation signaling technology, rather than as "stand alone" fourth generation systems.[10] There may be an opportunity to reduce the cost of signal systems and improve performance by moving to a fourth-generation approach.

Concept of Operations for a Jointless Broken Rail Detector

For railroads or transit systems who want to implement fourth generation signaling while retaining broken rail detection, this paper proposes a novel approach to track circuit implementation, focusing specifically on the need for detecting broken rails (an open circuit) rather than on detecting a shunt (short circuit.) Reliable shunting is not a central requirement for a track circuit whose main purpose is broken rail detection -- although in many cases, reliable shunting may still be obtained. Since trains are continuously reporting and updating their positions to PTC/ CBTC servers, the servers ***already know*** where trains are located. In a PTC/ CBTC context, the train's location reporting by the PTC/ CBTC system will be primary. Any additional location data reported by track circuits will only serve as a cross-check to further improve safety. Since shunts are harder to detect than open circuits, this may allow the use of simpler hardware and software, which should reduce the cost of track circuit installations.

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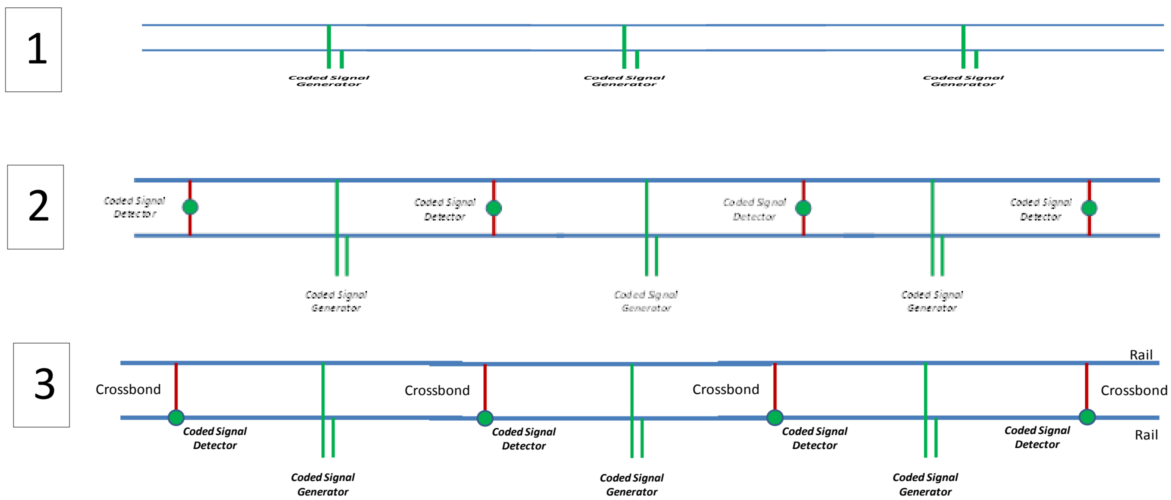
[7] If an alternating current (AC) based track circuit vice a direct current (DC) track circuit is used, the codes can even be picked up by inductive loops on board trains (the pulse-code signaling system or ATC) to provide signal indications inside the locomotive cab.
[8] "The programming language for Microlok application logic models and mimics a grid of electrical relays" [7]
[9] There are only a few exceptions to this, most notably the E-ATC PTC system which uses upgraded cab signals for providing all the PTC functionalities that are required by the Public Law 110–432 – the Rail Safety Improvement Act of 2008 (RSIA). However, ***most*** PTC systems, and all PTC and CBTC systems that are capable of stand-alone operation independent of track circuits or conventional signals, use some form of data radio telecommunications between the train and wayside. [8]
[10] Statutory requirements (the Rail Safety Improvement Act of 2018) in the United States to fully implement PTC by 1 January 2015 also appear to have contributed to railroad industry decision making to implement the less technically risky "overlay" PTC systems rather than pursue the implementation of more complex standalone PTC systems.

Any track circuit design that leverages the fail-safe principles of William Robinson's track circuit, will retain some ability to detect a shunt, so the impacts of shunting must be considered. Consistent with Robinson's fail-safe design principles [9] an electrical current must always be maintained for establishing a "safe" condition. In this regard, a jointless track circuit works the same way as any other track circuit has since 1870. The key difference is that jointless track circuits would either operate without predefined block limits, or else cross-bonds[11] would be used (instead of insulated joints) for partially limiting current flow beyond the established block boundaries.

Beacons or code generators would be placed at regular intervals along the track, as shown in all three variations of the system shown in Figure 1. Each beacon would broadcast a unique 8-or-16-bit digital code in both directions, so the circuit would operate as a center-fed track circuit. Receipt of these codes at any point up or down the line establishes the electrical continuity of the rails. Conversely, non-receipt of an expected code indicates either that the rail is broken or that the track is shunted.

Figure 1: Alternative Design Concepts for a Broken Rail Detector System



Receiver Installation

As shown in Figure 1, there are several choices for installing receivers or detectors in this system. Three possible options include mounting receivers: (1) on board the locomotive, (2) on a cross bond, or (3) underneath or on the side of a running rail on each side of each cross-bond.

- In Option (1), with a standard inductive cab-signal receiver on board locomotives broken rail detection could be based entirely on cab signals. As locomotives proceed down the track, the on-board unit would listen for codes from transmitters ahead. This requires use of AC beacons with enough amperage to be inductively picked up by an antenna located 6" above the rails.[12] However, trains may need more than a mile to stop, so compensating capacitors may be needed for boosting the signal. The issue of transmission range limits the practicality of this approach.
- In Option (2) detectors would be placed on cross-bonds[13]; in electrified territory, cross-bonds also carry traction currents. These detectors could be similar to today's DC or AC track circuit detectors which directly measure current flowing between the rails. Today, most coded DC track circuits require a minimum of 500mA (0.5 A) at the receiver although some crossing predictor receivers operate to a

[11] "S"-type impedance bonds are similarly used in audio frequency track circuit implementations for limiting current flow beyond block boundaries without needing insulated joints.
[12] Today, cab signal systems place up to 15 Amperes in the rails, which can reduce to 2 Amperes at the far end of the track circuit. An antenna on-board the locomotive can reliably detect 100 Hz codes in the rails down to a 2 Ampere minimum.
[13] Cross bonds intentionally short-circuit the track circuit at the block limits, so most of the signal current would use the cross bond for returning to its source. A small current may leak beyond the cross-bonds into the next signal block. This leakage is predictable and can generally be tolerated.

minimum of 100mA (0.1 A). These detectors usually have an adjustable resistance in a range of 0.25 to 2.00 ohms. Each detector would have a telecommunications link for reporting the codes it hears to the PTC or CBTC server, where the safety logic would reside.

- Option (3) is similar in concept to Option (2), except that instead of placing detectors on cross bonds, detectors would be mounted on the running rails themselves. These would either pick up an AC signal inductively as cab signal receivers do, or else mount an open-jaw magnetic flux concentrator on the rail and use a Hall-effect sensor for detecting coded DC or AC signals. The advantage of a rail-mounted detector is that it could largely mitigate "pre-shunt" problems[14] that until now have limited the use of jointless track circuits. It is reasonable to assume that a rail mounted sensor could work effectively down to a minimum of 0.5-1.0 A of current in the rail.

Beacon Operation

DC beacons have a longer range than AC beacons but can only be used on non-electrified tracks. In electrified territory, AC beacons must be used. To prevent two beacons from transmitting at the same time and interfering with one another's signals, three strategies are possible:

- Adopt a similar approach to that used in by ethernet. This would require each beacon to listen before transmitting its own signal; this reduces but does not eliminate collisions.
- Dispense with the need for the beacon to listen. Each beacon simply broadcasts its code at preset but irregular (randomized) intervals, so a small percentage of transmissions would be expected to collide.
- Use AC track circuits and avoid collisions by assigning different frequencies for each beacon. If frequencies are not reused within the range of the beacons, this eliminates the collision problem altogether.

Switches/Interlockings

Switches without insulated joints can pose a challenge, since electrical current must be prevented from using the rails of an adjacent track to bypass a potential rail break. Insulated joints can limit current flow, but "S"-Bonds and cross-bonds can also do this. Audio frequencies can be used for limiting signal range (alternative paths are usually longer than the direct path.) However, a full exploration of issues associated with switches and junctions is beyond the scope of this introductory paper.

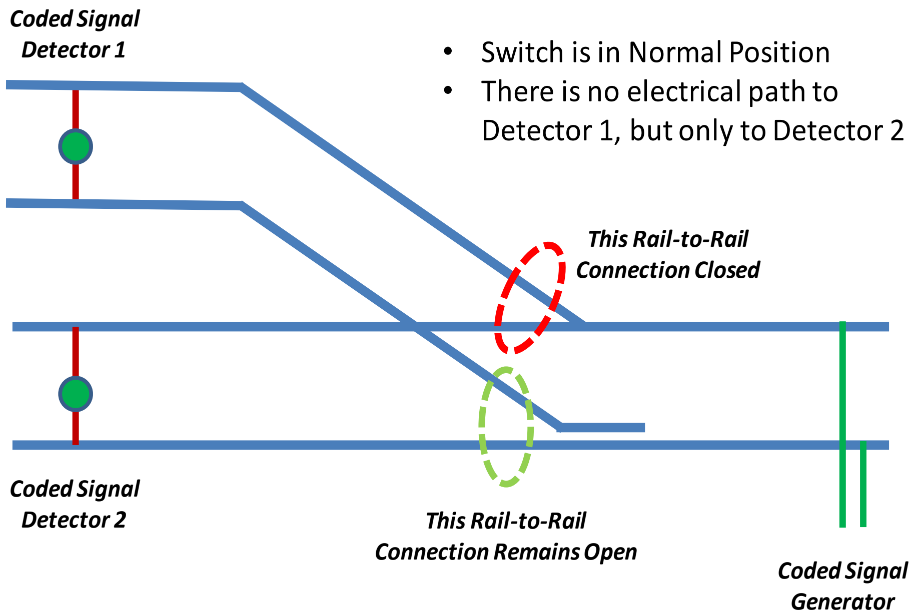
Even so, main tracks *between* interlockings often have sidetracks with hand-thrown switches. These sidetracks only need to be monitored to determine if they are out of normal position, while some other hand-thrown switches may need to be monitored regarding both normal and reverse position. This can be done without any insulated joints, by taking advantage of the natural ability of a railroad switch to also act as an electrical switch, as shown in Figure 2.

Track switches, by contacting switch points against the stock rail, can make or break an electrical circuit that properly directs the signal current along the intended path of a train. While the switch directs current towards the desired route, it also short-circuits current heading to or from the other branch. However, since the switch point against the rail does not make a reliable electrical connection, a switch point detector should be used for enhancing the connection between the point and rail.

Industrial switches only need to be wired for the normal position and only need a coded signal detector beyond the switch on the normal branch; siding switches must be wired for both the normal and reverse positions, and have coded signal detector units installed on both branches, as shown in Figure 2. The switch in normal position would direct the signal current towards Detector 2 along the intended path of travel; in reverse position, Detector 1 would receive the current instead.

[14] The term pre-shunting refers to the activation of a track circuit before a train reaches it. This will be detailed later.

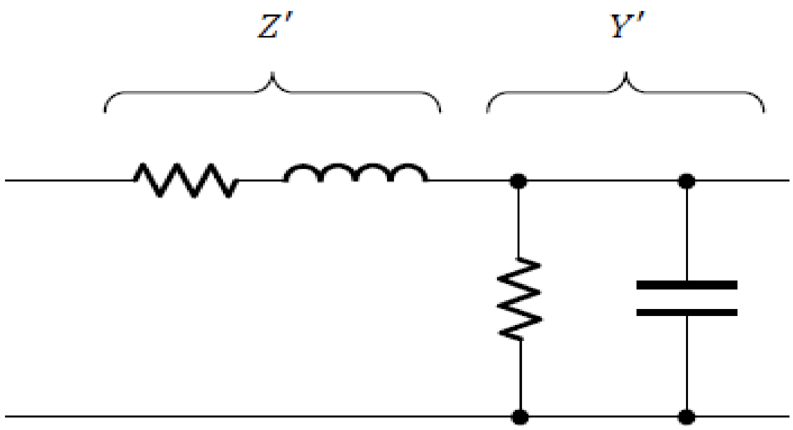
Figure 2: Track Switch Also Acts as an Electrical Switch



Mathematical Modeling of Electrical Current Flows

Since the early 20th century, transmission-line theory has been applied in track circuit analysis [10]. Following Landau [11], Figure 3 shows a typical element of a transmission line as applied to a rail track. The model includes elemental series (rail) impedance Z′—with resistance and inductance—and elemental shunt (ballast) admittance Y′—with conductance and capacitance. These characteristics are assumed to be uniformly distributed along the entire track circuit.

Figure 3: Track Segment Modeled as a Transmission Line



The transmission line equations are defined as a system of differential equations, but Landau [11] derives a solution[15] with two equations, which define the "feed-end" voltage *v(L)* and current *i(L)* in terms of "relay-end" voltage *v(0)* and current *i(0)*. The two equations are:

$$v(L) = v(0) \cosh \sqrt{ZG} + i(0) \sqrt{\frac{Z}{G}} \sinh \sqrt{ZG}$$

$$i(L) = i(0) \cosh \sqrt{ZG} + v(0) \sqrt{\frac{G}{Z}} \sinh \sqrt{ZG}$$

For a DC track circuit rail impedance *Z* is the same as rail resistance *R*. For an AC track circuit, impedance would be some multiple of rail resistance. Ballast conductance *G* is the reciprocal of ballast resistance *B*. Replacing Z with R, and G with 1/B, the equations can be rewritten as follows:

$$v(L) = v(0) \cosh \sqrt{\frac{R}{B}} + i(0) \sqrt{RB} \sinh \sqrt{\frac{R}{B}}$$

$$i(L) = i(0) \cosh \sqrt{\frac{R}{B}} + v(0) \frac{1}{\sqrt{RB}} \sinh \sqrt{\frac{R}{B}}$$

By inspection of these equations it is apparent that two terms appear several times in the equation. These terms are based on constants and can be pre-calculated. These are:

$$\Gamma \text{ (Gamma)} = \sqrt{\frac{R}{B}}$$

$$Z_o = \sqrt{RB}$$

If Γ and $Z_{o,}$ are pre-calculated, the equations can be simplified as follows:

$$v(L) = v(0) \cosh \Gamma + i(0)\ Z_o \sinh \Gamma$$

$$i(L) = i(0) \cosh \Gamma + v(0) \frac{1}{Z_o} \sinh \Gamma$$

[15] Equations #27 and #28 in Landau [11].

Example Calculation #1 [16] – 23,000’ DC Track Circuit w/Shunt at the Detector

The performance of an un-shunted 23,000’ DC track circuit under wet ballast conditions[17] with a 7 A, 4 V constant power supply has been modeled as follows. These results are summarized in Figure 4:

- In wet conditions (corresponding to 3 Ω/k-ft ballast resistance) the power supply at the feed end will inject 7 A at 1.647 V. From this, the overall resistance of the track circuit is 0.235 Ω.
- For a conventional track circuit, the feed voltage maximum should be restricted based on the wet ballast setting of 1.647 V. Throttling the maximum voltage back from 4V to 1.647 V will not affect the circuit in wet ballast conditions but limits the amount of current increase in dry ballast conditions. Doing this will improve the shunt sensitivity of the track circuit.
- Of the original 7 A, only 1.12 A (16%) reaches the detector in wet ballast conditions, and voltage at the relay end falls to 0.28 V. Therefore, under wet ballast conditions, 5.9 A (84% of the feed amperage) leaks across the ballast before it even reaches the detector.
- Under dry ballast conditions,[18] the value of 3 Ω/k-ft ballast resistance (in cell B9) is changed to 15 Ω/k-ft. Limiting the feed voltage to 1.647 V (its value in wet ballast conditions) results in a feed current of 3.61 A in an un-shunted condition. With dry ballast, the resistance of the overall track circuit nearly doubles to 0.46 Ω, while 2.04 A or 57% of feed current reaches the detector.
- With a 0.06 Ω shunt,[19] 0.36 A and 0.60 A reaches the detector under wet and dry ballast conditions, respectively.

Figure 4: Shunting Sensitivity of 23,000-foot DC Track Circuit

Circuit Condition	Amps @ Detector
Dry Ballast UnShunted	2.04
Wet Ballast UnShunted	1.12
Detector Threshold	***0.86***
Dry Ballast Shunted	0.60
Wet Ballast Shunted	0.36
Broken Rail	0.00

$$\frac{(1.12-0.60)}{0.60} = 87\%\ \text{Detector Margin}$$

[16] An Excel workbook https://chipkraft.github.io/AREMA%20Broken%20Rail%20for%20PTC%20Examples.xlsx contains all the calculations for this paper. If the direct download link does not work on your computer, instead try https://github.com/chipkraft/chipkraft.github.io which displays a menu of available files. Select the file name above and Github will display a second page. A download button is available on that page.

[17] The first worksheet in this workbook, “***Ex 1 - Wet Ballast UnShunt***” calculates:

- Γ (Gamma) and Zo (cells B12 and B13).
- the current at the relay end using Ohms Law (cell D16).
- voltage and amperage at the feed end (cells C15 and D15).

Required inputs are entered in the highlighted yellow cells. For example:

- Track circuit length is 23,000 feet (cell B15)
- Rail resistance is 0.0184 Ω/thousand feet (cell B8) (both rails)
- Ballast resistance of 3 Ω/thousand feet (for wet ballast) (cell B9)
- Resistance of the detector 0.25 Ω (Cell H10).[17]
- Voltage across the detector (cell C16)[17].
- Shunt/detector resistance (cell E16)

[18] See the worksheet “***Ex 1 - Dry Ballast UnShunt”***

[19] Shunted conditions for wet and dry ballast are modeled in ***Ex 1 - Wet Ballast Shunted*** and ***Ex 1 - Dry Ballast Shunted***

Figure 4 illustrates how track circuits operate under a broad range of environmental conditions. As ballast resistance varies from 3 to 15 Ω, current reaching the detector ranges between 1.12 – 2.04 A, and if a shunt is present, from 0.36 – 0.60 A. ***For the proper functioning of the track circuit, it is essential that these two ranges do not overlap.***

The Detector Threshold can be set between the two ranges, for example, it is set to 0.86 A in Figure 4. With this setting, a minimum current of 0.86 A would be needed to support a determination that the block is "safe." If current reaching the detector falls to a value less than 0.86 A then the block is either occupied by a train, a rail is broken or the power supply has failed. The circuit "fails safe" since if the feed power supply were interrupted; no current would reach the detector.

In Figure 4 there is an 87% Detector margin based on a feed volt limit of 1.647 V. This is an excellent result since a 30% Detector margin[20] is considered the minimum acceptable [12]. If the 1.647 V feed voltage limit were ***not*** enforced[21], current through the shunter detector in dry ballast conditions would rise from 0.60 A to 0.95 A. This would reduce the Detector margin to just 18% which is not acceptable. For conventional track circuits, this further illustrates the importance of proper calibration of the feed voltage for optimizing the shunting sensitivity.

Example Calculation #2 – 23,000' DC Track Circuit w/Shunt Anywhere

The second example generalizes the 23,000' DC track circuit analysis, by dividing the circuit into segments.[22] By doing this, voltage and current can be measured anywhere along the track, and also a shunt can to be modeled anywhere along the track, not just at the end:

- Figure 5 shows how current and voltage changes along a 23,000' DC ***un-shunted*** track circuit, with a ballast resistance of 3 Ω/k-ft, which represents wet ballast. Feed current is 7 A at 1.65 V, the same as in Example 1. The overall resistance of the track circuit is 1.65/ 7 = 0.236 Ω. Current drops to 1.12 A at 0.28 V by the time it reaches the relay end.

- In Figure 6, a 0.06 Ω shunt moves from the feed end (Zero) toward the detector (at 23,000'.) As it does so, current measured at the detector rises from 0.23 A to 0.36 A, while the voltage measured at the feed end rises from 0.33 V to 1.56 V. The overall resistance of the track circuit increases from 0.048 Ω to 0.226 Ω as the shunt moves away from the feed towards the detector.

[20] From [12]: "*Residual voltage can arise in a number of different ways or as a combination of those ways. The factors governing the value obtained at any instant in time are themselves very variable (e.g. weather, train positions and traction power loading). It is therefore necessary to provide a factor of safety to cater for these unknowns. . . A wrong side failure will not occur unless the level of extraneous voltage attains that necessary to influence the operation of the track relay (i.e. the drop-away value). The general upper working limit for residual relay voltage is therefore set at 30% of the drop-away value; below this level, the inability to attain the drop-away value is assumed and the situation is regarded as safe; above this level, it is assumed unsafe unless enhanced supervision or monitoring can demonstrate that the interference is incapable of attaining the drop-away value*."

[21] The excel workbook also includes a set of "sensitivity" worksheets

[22] The sheet ***Ex 2 - 23000 Multi-Part*** divides the track circuit into ten segments of 2,300' each. The sheet also adds an "AddCurrent" column showing how much current uses a shunt located at the beginning of each segment. Working from the relay end towards the feed end, any additional shunt current has to be added to the current returning from the relay end so that the current flow always increases moving towards the feed end of the track segment. It also adds one technical feature, which is an optional multiplier on DC rail resistance. Although it is not used in this example, this multiplier is available for modeling jointed rail or AC track circuits, which have higher impedance to current flow than do DC currents in welded rails.

Figure 5: Voltage and Current along an Un-shunted 23,000-foot DC Track Circuit

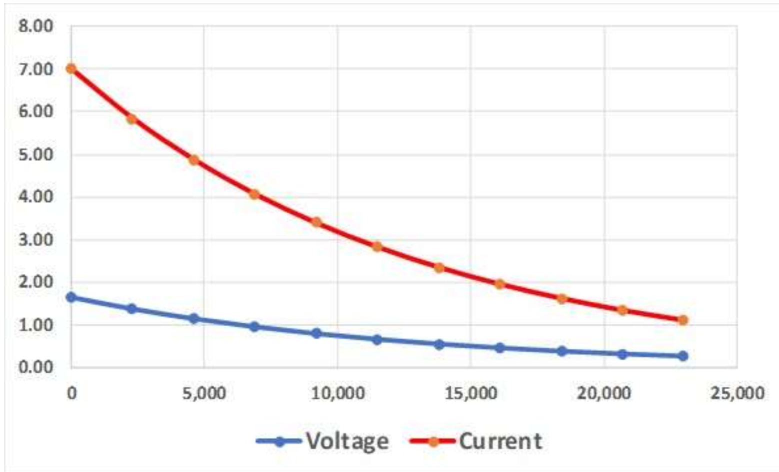
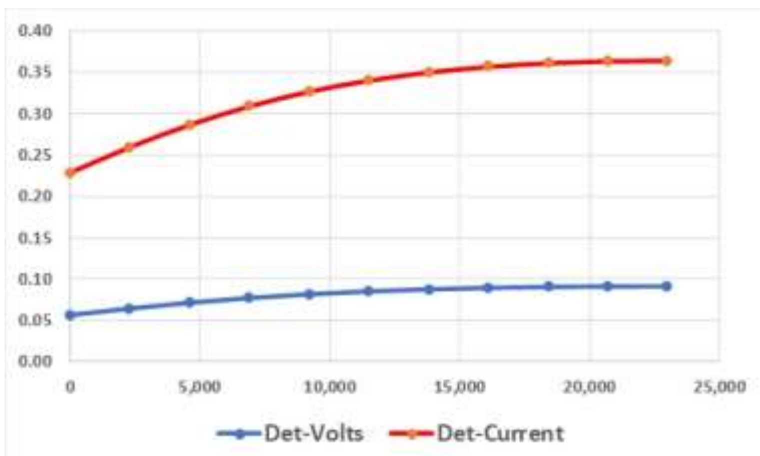


Figure 6 shows that a shunt located directly over the power supply is the most effective at reducing detector current; current in the detector increases as the shunt approaches the detector. Therefore, a shunt directly over the detector is the most difficult for a track circuit to detect.

Figure 6: Detector Voltage and Current Based on the Location of a 0.06Ω Shunt



In the above discussion, current and voltage have been measured at both the feed and detector ends. However, traditional track circuits only utilize the current at the detector to determine the condition of the track circuit – these detectors have no knowledge of what may be happening at the feed end. If however, the data collected at the detector and feed end could be combined using telecommunications, this provides a more complete and integrated view of the condition of the track circuit.

This can be done by normalizing detector amperage by feed resistance as shown in Figure 7, which restates Figure 4:

- For wet ballast, feed resistance has already been cited as 0.236 Ω for an un-shunted circuit, and 0.226 Ω for a circuit shunted at the detector.
- The corresponding feed resistance values for dry ballast are 0.446 Ω for an un-shunted circuit, and 0.376 Ω for a circuit shunted at the detector.

Figure 7: Enhanced Shunting Sensitivity of 23,000-foot DC Track Circuit

Circuit Condition	Amps @ Detector	Feed Ohms	Amps per Ohm
Dry Ballast UnShunted	2.04	0.446	4.58
Wet Ballast UnShunted	1.12	0.236	4.75
Detector Threshold	***0.86***		***3.17***
Dry Ballast Shunted	0.60	0.376	1.58
Wet Ballast Shunted	0.36	0.226	1.61

$$\frac{(4.58 - 1.61)}{1.61} = 184\% \text{ Detector Margin}$$

Dividing detector amperage by the feed resistance in Figure 7, this shows that the shunting sensitivity of track circuits can be substantially improved by merging data generated by both the transmitter and receiver units. Normalization provides a means whereby the track circuit can adjust itself to changing ballast conditions. In Figure 7:

- On an Amps basis, the detector values for dry vs. wet ballast spread by an almost 2:1 margin (2.04 vs 1.12 A) for an un-shunted circuit, and they have a similar wide spread (0.60 vs 0.36 A) for a shunted circuit.
- However, normalizing Amps per Ohm causes the values to cluster tightly together depending only on the shunt condition of the circuit (e.g. 4.58 vs 4.75 for un-shunted, and 1.58 and 1.61 for a shunted circuit.) Because of this tighter clustering, the track circuit is better able to discriminate a shunted vs. non-shunted condition regardless of ballast conditions.

In this example, normalization can ***more than double*** the detector margin from 86% to 184%. However, calculation of normalized detector margins requires that both detectors and transmitters be linked into a telecommunication network, and that they share their measurements on a real time basis with a PTC or CBTC server, which becomes responsible for implementing the vital safety calculations. The same approach can also be used for jointless track circuits, as will be shown in the next example.

Example Calculation #3 – 6,000' Jointless DC Track Circuit

Example 3 models a 6,000' jointless DC track circuit[23] as shown in Figure 8. Since current is fed in both directions, a strong 15 A / 4 VDC power supply must be used. Since no insulated joints are used, detectable levels of current[24] are likely to reach the 3rd or 4th detector even under wet ballast conditions.

Figure 8 only shows the ***left half*** of the circuit; the same circuit extends towards the ***right side*** as a mirror image. However, only the left side is subject to shunting; the right side remains un-shunted:

- In an un-shunted condition, the 15 A feed current divides equally due to symmetry, so each side of the track circuit receives 7.5 A.
- The presence of a shunt reduces the track circuit's resistance, so the left and right sides are no longer balanced. More current flows towards the shunted (left) side, and less current towards the un-shunted (right) side. This reduces the current in the rail on the right-side, even as current measured on the left side continues to increase.

[23] The Excel sheet, ***Ex 3- JLess Wet Ballast Noshunt*** has the same multi-layered structure that divides the track circuit into ten segments. Mathematically the formulation is the same as for Example 2; only some of the input data is set up differently.

[24] As previously noted, standard track circuit receivers (mounted on cross bonds) can detect a signal down to a minimum of 0.1-0.5 A. As a result redundancy is built-in to this design, since multiple detectors can back-up one another should any signal generator or detector fail.

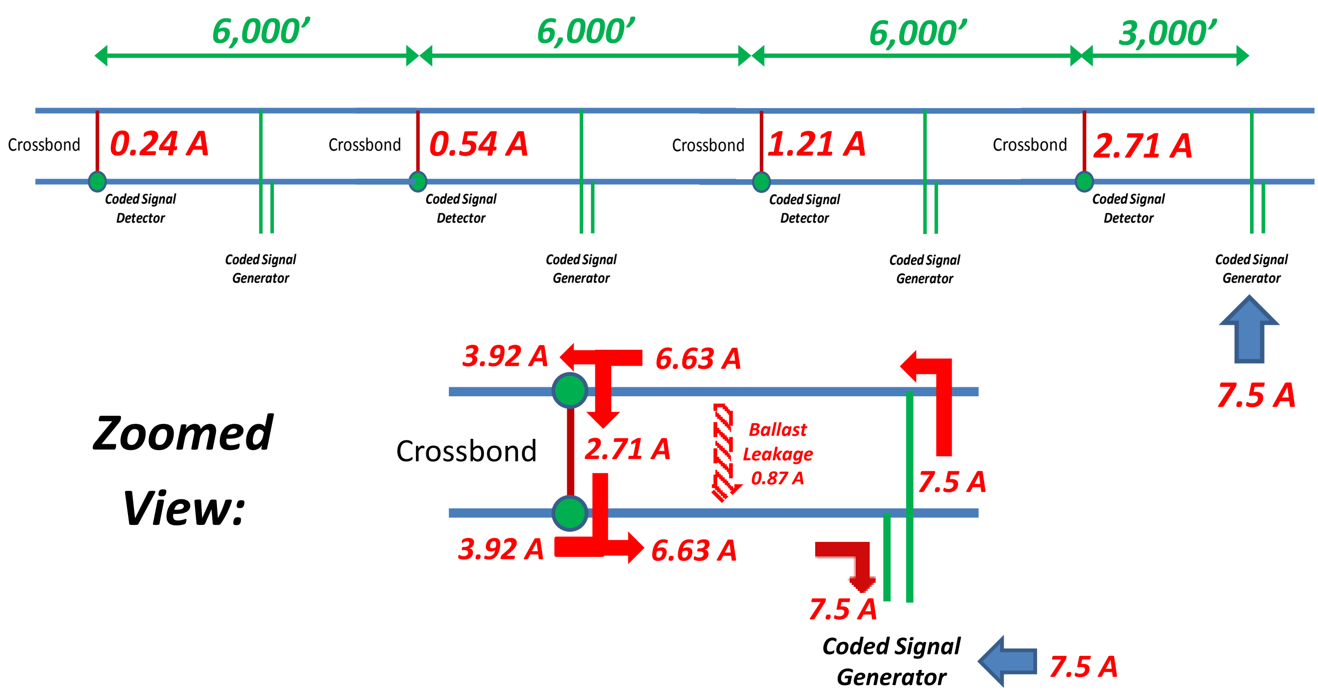
The bottom part of Figure 8 shows an expanded view of the current flowing within the first 3,000' of the circuit. At each cross-bond, each detector will only receive a fraction of the current flowing in the rails. The remaining current will continue beyond the detector; it eventually leaks through the ballast or passes through a subsequent detector. As a result, the current flowing in the rails is always greater than current flowing in the cross bonds. For the un-shunted circuit shown in Figure 8:

- 7.5 A is fed into the track at 1.065 V; the resistance of the left side is therefore 0.142 Ω. The right side of the circuit will absorb another 7.5 A, so the overall resistance of both sides of this track circuit is half of 0.142 Ω, or 0.071 Ω.
- 0.87 Amps leaks across the ballast before it reaches the first detector, and 6.63 A is still in the rail upon reaching the first detector, and the voltage across the rails is 0.678 V.
- With an assumed detector resistance of 0.25 Ω, 2.71 A will be drawn through the cross bond and the remaining 3.92 A will continue in the rails past the first detector. From a modeling perspective, this 3.92 A at 0.678 V becomes the feed current and voltage for the next layer of calculations using the Telegrapher's equations.

As shown, there are five locations at each crossbond where current can be measured: two locations on each rail (both sides of each crossbond) as well as on the crossbond itself. Only two detectors are needed to be able to calculate all five values. Two detectors could be placed on the rails, or one on a rail and one on a crossbond.

Figure 9 shows the effect of adding a 0.06 Ω shunt, simulating a train moving from left to right. It starts 9,000' left of the signal generator moves towards the right until reaching the signal generator itself at location zero.[25] This figure shows the current in both the rails and crossbonds, as measured at the first detector on both the left and right side, which is 3,000' from the generator. The top two curves show current measured in ***rails***; whereas the bottom two curves show current in the ***crossbonds***.

Figure 8: Electrical Model of a Jointless Broken Rail Detector

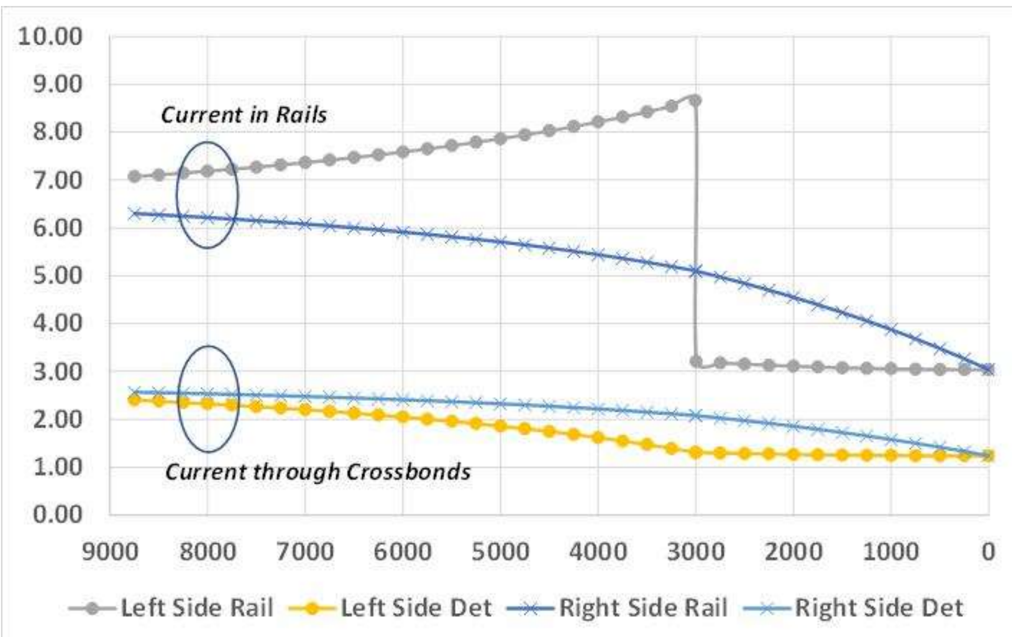


[25] The horizontal axis in Figure 9 has been reversed so the orientation of Figure 9 matches Figure 8 The power supply is on the right side.

Of particular interest is what happens to the current in Figure 9 as a train approaches and then crosses over the first crossbond, at a distance of 3,000' from the generator.

- In an un-shunted condition, detectors on both side of the code generator receive 6.63 A.
- As a train approaches ***from the left***, current in the rails on the left (or shunt) side will start to rise above 6.63 A -- while current reaching the detector on the far side slowly drops as the shunt approaches the generator. Since the shunt has low resistance it draws current towards itself, and away from the detector on the far side.
- Once the shunt passes the crossbond at the 3,000' mark, current measured in the rails at the left crossbond drops precipitously, since the shunt intercepts current before it can reach the detector. Furthermore once the current drops it remains at a practically constant level, until the shunt reaches the feed or signal generator. The current on the ***opposite*** side rail detector and in crossbonds continues to decline, but only gradually as the shunt passes over the crossbond.[26]
- As the shunt approaches the generator, current in rails and crossbonds equalizes on both sides.
- Once the shunt passes over the power supply, the process reverses on the other side.

Figure 9: Current in Rails and Detectors as the Shunt Moves



In Figure 9, as the shunt approaches the crossbond at 3,000', the current in the left-side rail ***rises*** while the current in the left-side crossbond ***falls***. As a result, an approaching train ***will not*** pre-shunt a jointless track circuit if the current measurement is taken in the ***rail***. It may however pre-shunt the circuit if the current measurement is taken in the ***crossbond***. This is the reason why a rail-mounted detector is preferable to a crossbond-mounted one for use with jointless track circuits.

With a minimal 0.06 Ω shunt,[27] the current in the rails never drops below 3 A, and in the crossbonds below 1.3 A. With a light shunt, current in the rails and crossbonds may remain at a detectable level even if the track circuit is shunted. In this case the rail integrity can still be confirmed even if the circuit is shunted, since even a minimal level of current is enough to prove that the circuit is complete.

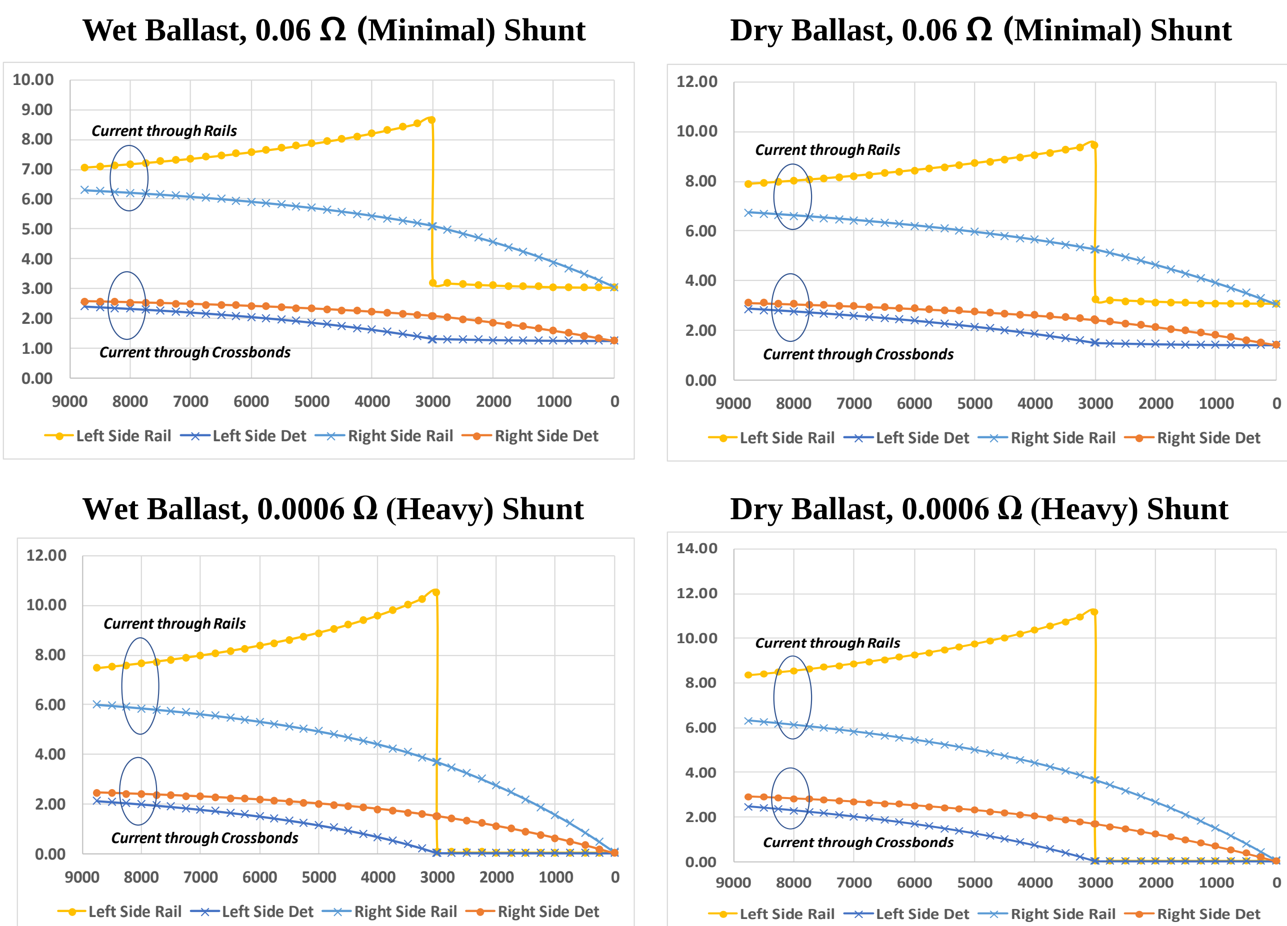
[26] This weak shunt response of cross bond-mounted current detectors explains why insulated joints are needed for delimiting block boundaries if traditional they are used are used.

[27] The shunting value of 0.06 Ω is the minimum legal requirement of 49 CFR § 236.56. See [13].

However, a stronger shunt may reduce current below the minimum detectable level which means that the broken rail detection may no longer be effective if the circuit is shunted.[28] A full analysis of a conventional track circuit requires that the circuit be modeled ***four*** times: in wet and dry ballast conditions; both un-shunted and shunted. By comparison, a full analysis of a jointless circuit requires ***six*** assessments: in wet and dry ballast conditions as before; un-shunted, shunted with a minimal 0.06 Ω shunt, and shunted with a maximal or heavy shunt as close to as computationally practicable. For this analysis a value of 0.0006 Ω has been used. Figure 10 shows the curves resulting from the four shunted circuit analyses[29] for the 6,000-foot DC track circuit on Example 3. This reflects wet and dry ballast, and a minimal vs. heavy shunt.

Figure 11 shows the currents and detector ratios for the 6,000' Jointless DC Track Circuit based on current flowing through the left-side rail detector, and it also includes the normalization calculation based on the overall resistance of the track circuit as measured at the source. On this basis the detector ratios are excellent: for the minimal shunt case, the amperage for the shunted track circuit is approximately 3.2 A, whereas for the un-shunted circuit it is 6.6 A. The un-shunted current is 105% greater than the shunted current; this substantially exceeds the 30% minimum required, so this track circuit looks good at a 6,000' length.

Figure 10: Shunting Curves for a 6,000' Jointless DC Track Circuit



[28] It should be noted however that the same is true for conventional track circuits as well, there is no active broken rail detection within a shunted block.

[29] The un-shunted circuit analysis does not produce a curve, since there is no shunt to move, but only a single value for the amperage at the first detector and ohms of the un-shunted circuit. This is the reason why curves are not shown for the un-shunted case.

However, there is one additional factor to consider, and that is the question of what is happening to current in the rail detector on the right-hand (opposite) side. This is essential since the shunt criteria are based on the minimum current from either the left or right-side detectors. As a train approaches on the left side it will attract a greater share of current towards itself:

- Immediately before the train passes over the left crossbond (assuming a strong 0.0006 Ω shunt and wet ballast) the current in the left-side rail detector will rise to 10.5 A; while current in the right-side detector will fall to 3.7 A.
- As soon as the train passes over the left crossbond current in the left-side detector will precipitously fall to less than 0.05 A while current in the right-side detector will remain at 3.7 A.

Figure 11: Detector Margins for a 6,000' DC Jointless Track Circuit

Heavy Shunt

Circuit Condition	Amps @ Detector	Feed Ohms	Amps per Ohm
Dry Ballast UnShunted	7.29	0.083	87.52
Wet Ballast UnShunted	6.63	0.071	93.47
Detector Threshold	***N/A***		***N/A***
Dry Ballast Shunted	0.06	0.042	1.39
Wet Ballast Shunted	0.06	0.039	1.56

$$\frac{(6.63 - 0.06)}{0.06} = 10{,}950\%\ \text{Detector Margin Amps only}$$

$$\frac{(87.52 - 1.56)}{1.56} = 5{,}510\%\ \text{Detector Margin Amps/Ohm}$$

Minimal Shunt

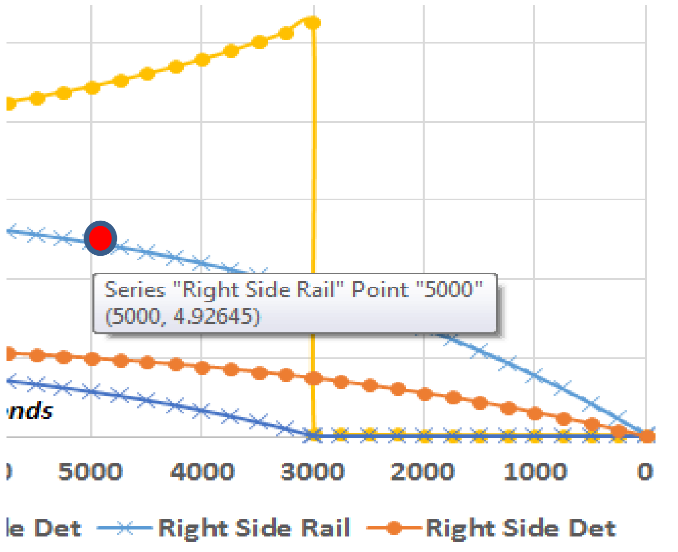
Circuit Condition	Amps @ Detector	Feed Ohms	Amps per Ohm
Dry Ballast UnShunted	7.29	0.083	87.52
Wet Ballast UnShunted	6.63	0.071	93.47
Detector Threshold	***4.94***		***73.74***
Dry Ballast Shunted	3.24	0.060	54.01
Wet Ballast Shunted	3.21	0.055	58.81

$$\frac{(6.63 - 3.24)}{3.24} = 105\%\ \text{Detector Margin Amps only}$$

$$\frac{(87.52 - 58.81)}{58.81} = 49\%\ \text{Detector Margin Amps/Ohm}$$

The problem is that the current in the right-side detector at 3.7 A is less than the detector threshold of 4.9 A. This means that a heavy shunt will pre-shunt the right-side rail detector by starving it of current, even before the train reaches the 6,000' detection section. As shown in Figure 12, this will occur when the shunt reaches a position of 5,000' left of the detector or 2,000' before reaching the left-side detector and crossbond. This problem cannot be remedied by reducing the detector threshold because it then becomes too close to the upper value of 3.24 A which flows through the detector in the Dry Ballast Shunted condition.

Figure 12: Pre-Shunt of Right-Side Detector at a distance of 5,000' from the Generator



The solution to this problem is to use "Amp per Ohm" normalized thresholds. The feed resistance of the track circuit vs. the current flowing through the un-shunted right side of the track circuit are linearly related. So even as the current flowing to the right-side drops, the overall resistance of the track circuit reduces at exactly the same rate.

The Amps per Ohm reading at the right-side detector always remains constant retaining its un-shunted value in the range of 87 to 94 Amps per Ohm, and this value does not depend on the position of the shunt on the left side. By comparison, as soon as the shunt passes the crossbond, the Amps per Ohm reading of the left-side detector will immediately fall into the range 0-59, although as the generator is approached it will return to its un-shunted value of 87-94. ***As a result, by using the Amps per Ohm normalization in conjunction with the current readings, the problem of pre-shunting the right-side detector can be eliminated.*** It also allows the two sides of the center-fed track circuit to be treated independently if a rail current detector were installed at the feed location to determine which direction the current is going, Because of this a 6,000' crossbond spacing can actually give a 3,000' detection block. This leads to the conclusion that:

- For conventional track circuits, the use of Amps per Ohm thresholds is optional and can ***improve*** the detection margins
- For jointless track circuits, use of Amps per Ohm thresholds is ***required***.

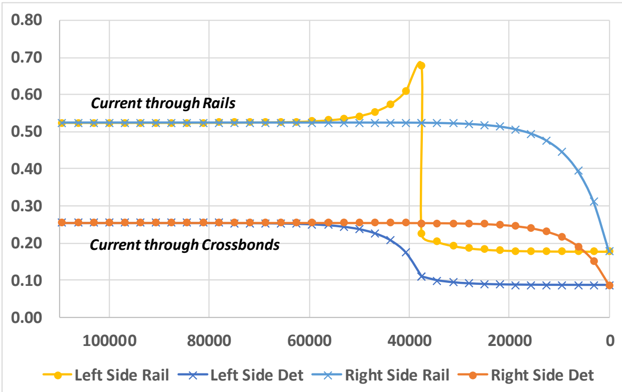
Example Calculation #4 – 75,000' Jointless DC Track Circuit

The fourth case study will explore a rather extreme example to show what happens if the jointless track circuit concept is pushed to its limits. The shunting curves for this case are shown in Figure 13, and the detector margin calculation is summarized in Figure 14.

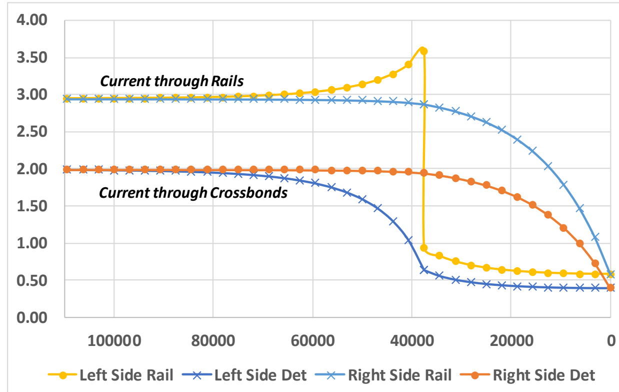
The general shape of the curves is similar to that of Example 3, but shows a greater sensitivity to ballast conditions. Under dry ballast conditions for an un-shunted track circuit, nearly 3.0 Amps reaches the detector at a 37,500' distance; but with wet ballast this falls to just 0.5 A. With wet ballast this is approaching the minimum detectable current, and so a 75,000' foot track circuit is obviously reaching the maximum limit of the track circuit length.

Figure 13: Shunting Curves for a 75,000' Jointless DC Track Circuit

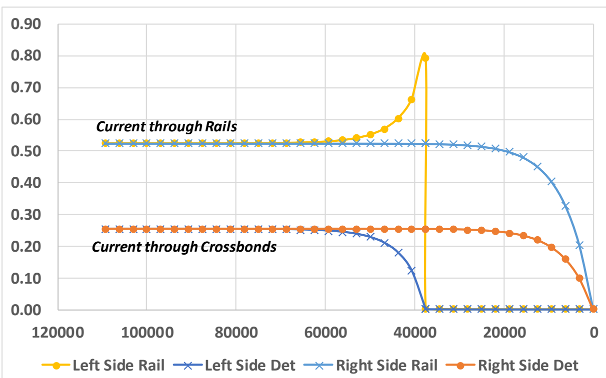
Wet Ballast, 0.06 Ω (Minimal) Shunt



Dry Ballast, 0.06 Ω (Minimal) Shunt



Wet Ballast, 0.0006 Ω (Heavy) Shunt



Dry Ballast, 0.0006 Ω (Heavy) Shunt

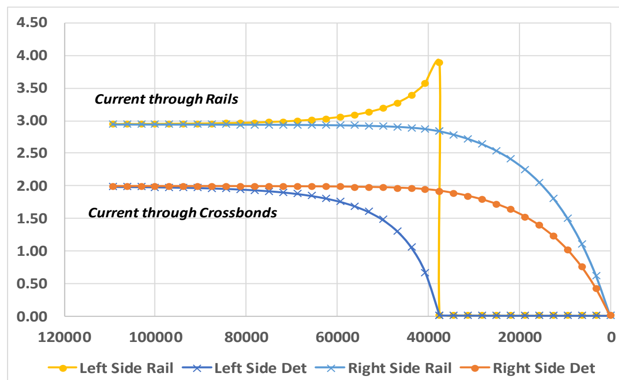


Figure 14: Detector Margins for a 75,000' DC Jointless Track Circuit

Heavy Shunt

Circuit Condition	Amps @ Detector	Feed Ohms	Amps per Ohm
Dry Ballast UnShunted	2.94	0.244	12.06
Wet Ballast UnShunted	0.52	0.117	4.47
Detector Threshold	***N/A***		***N/A***
Dry Ballast Shunted	0.01	0.235	0.06
Wet Ballast Shunted	0.00	0.117	0.03

$$\frac{(4.47-0.06)}{0.06} = 7{,}350\%\ \text{Detector Margin Amps/Ohm}$$

Minimal Shunt

Circuit Condition	Amps @ Detector	Feed Ohms	Amps per Ohm
Dry Ballast UnShunted	2.94	0.244	12.06
Wet Ballast UnShunted	0.52	0.117	4.47
Detector Threshold	***OVERLAP***		***4.21***
Dry Ballast Shunted	0.94	0.238	3.95
Wet Ballast Shunted	0.22	0.117	1.92

$$\frac{(4.47-3.95)}{3.95} = 13\%\ \text{Detector Margin Amps/Ohm}$$

From a shunting perspective the Amperage criteria already overlap, since 0.92 A for dry ballast (shunted) already exceeds the 0.5 A that reaches the detector in wet ballast conditions, the traditional Amperage threshold criteria are already overlapping. Amps per Ohm normalization eliminates this overlap, but only results in a 13% detector margin, which is less than the minimum required 30%.

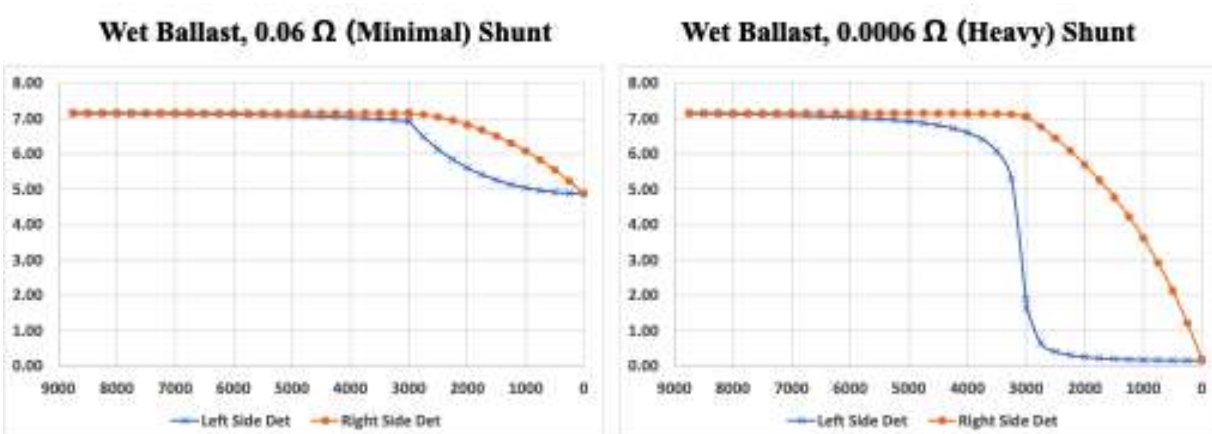
This track circuit can functional only in dry ballast or with a very heavy shunt. Its length should be reduced for increasing the signal strength (amperage) reaching the detectors, and for improving the detector margin to achieve the minimum 30% requirement.

Example Calculation #5 – Low Impedance Crossbonds

The fifth and final example will assess the potential of an alternative system embodiment that only uses current detectors on crossbonds. Very low-impedance crossbonds, such as copper cables directly connecting the two rails (e.g. 0.002 Ω) are needed, with a detector (such as a Hall Effect device or Rogowski Coil) mounted on each crossbond. Figure 15 shows a photo of a crossbond cable in an actual track. This type of track circuit could ***only*** be used for broken rail detection – it could ***not*** effectively detect a shunt. The length of the track circuit is 6,000', as before. Figure 16 shows the shunting curves for this configuration, for both a minimal .06 Ω and a hard .0006 Ω shunt.

Figure 15: Crossbond Cable Installed in a Track

Figure 16: Shunting Curves for a 6,000' Jointless DC Track Circuit (Low Resistance Crossbond)



Since only crossbond mounted detectors are used in the example, the results for rail-mounted detectors have been removed from the charts. However, since low resistance crossbonds practically short-circuit the track, measurements in the rail would be very similar to those seen in the crossbonds. As shown in Figure 16, with a low-resistance crossbond:

- A relatively light shunt of .06 Ω would only reduce current in the detector from 7 A down to about 5 A. This circuit could still function as a broken rail detector even while shunted.
- A strong shunt of 0.0006 Ω will pre-shunt the left-hand detector as current falls from 7 A to about 2 A when the train reaches the cross-bond at 3,000'. Although the circuit is pre-shunted in this example, enough current still reaches the detector so broken rail functionality can remain active until the train passes over the cross-bond. Shortly ***after*** the train crosses over, current may reduce to undetectable levels -- but by then, the train has already entered into the block.

The critical outcome to be prevented would be a track circuit signaling a broken rail due to a pre-shunt. If this occurs the circuit could trigger a false restrictive signal indication just when a train is about to enter a new detection block. To prevent a pre-shunt, enough current needs to be able to reach the detector to keep the circuit clear, at least until the train has actually entered into the block. The model analysis suggests, however, that a very low resistance crossbond can effectively prevent most pre-shunting.

With a low resistance crossbond, any pre-shunt that does occur would generally only happen within a few hundred or maybe thousand feet ahead of a train. The PTC or CBTC system server could use received train location data to determine whether any apparent broken rail is a legitimate safety issue or only the result of a pre-shunt. By allowing a small buffer margin a pre-shunt just ahead of a train would be filtered out, rather than being sent to the train. Of course, the best way is to eliminate the issue of pre-shunts altogether, and this could be done by mounting current detectors on the rails instead of on crossbonds. However, this illustrates how PTC or CBTC train location data might integrated with track circuit data, to enable the development of a lower cost and more efficient track circuiting approach which also eliminates the need for insulated joints.

Conclusions and Next Steps

This paper has presented several new concepts for jointless track circuits. A mathematical model has been used to validate the concepts and to predict the system performance. The research has suggested new ways for integrating track circuits with PTC and CBTC, and addresses the potential of this new approach for both broken rail detection and shunt detection.

The pursuit of alternatives to insulated joints is a worthwhile goal, and could itself be an important benefit. In both light and heavy-axle loading situations, insulated joints represent a maintenance liability and become a potential point of failure of the track and signal infrastructure. In electrified systems in particular, insulated joints require the use of expensive impedance bonds. DC electrification can magnetize insulated joints, requiring additional regular maintenance to prevent signal failures. Broken rails within insulated joints are usually not detected by the signal system. As a result, every insulated joint that can be eliminated further reduces the likelihood of an undetected broken rail failure.

A significant limitation of jointless track circuits has historically been the pre-shunt issue. To resolve this limitation in audio frequency AC track circuits, S-Bonds have been used which act essentially as the equivalent of electrical insulated joints. A second key issue is the normalization of detector current based on feed resistance, which is the key to preventing a pre-shunt by the detector on the right-hand side of the track circuit. However, this work has shown that DC jointless track circuits could be feasible if the detectors could be moved away from the cross-bonds and mounted on the rails instead.

The realization that a rail-mounted current detector could work emerged initially from an understanding of how cab-signal system work. Cab Signal systems rely on picking up coded signals from the rails, which proves the technical feasibility. Preliminary discussions with manufacturers of DC hall-effect sensing equipment have suggested the feasibility of developing a similar rail-mounted DC current detector as well.

While this paper shows the feasibility of this new approach, there are additional research areas that needed to be more fully developed to support implementation and deployment. These include:

- Electrical modeling of more complex track configurations, such as passing sidings and interlocking junctions, which could potentially offer multiple paths for current flow.
- Electrical modeling of AC track circuits, including power frequency up to audio frequency track circuits, and integration of these with electrification systems.
- Further refinement and documentation of basic electrical track modeling parameters, including for example resistance and impedance, capacitance and reactance of rail track and signal appliances in various configurations and environmental conditions.

Information gained from this effort will provide additional data to allow

- Development of detector technology, including both rail mounted and crossbond mounted devices that can monitor current flows without interfering with the flows.
- Development of cost-effective means of linking detector devices with the PTC data network including, for example, the availability of low cost solar and wireless technologies.
- Development of PTC and CBTC server functionality changes for integrating detector data with train control functionality.

It will also be necessary to determine deployment requirements and strategy for this new approach in the railroad industry, especially with regard to helping to close “gaps” in current PTC and signal system coverage in the safest, most timely, and cost-effective manner:

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