How Track Circuits detect and protect trains

Jodi Scalise
November 2014
railwaysignalling.eu, Italy
jodi.scalise@railwaysignalling.eu

ABSTRACT
Track circuit is the fundamental method of train detection. The first track circuit, based on a DC technology, has been invented at the and of nineteenth. Over the years, the continuous technological development has enabled to realize track circuits in an increasingly performing way by using AC technology and modulations, but the basic principle for train detection is still the same.
An alternative approach is the Axle Counter system, which uses a “check-in/check-out” logic. By comparing the result for the axles counted in a block section with the result for those counted out, it is possible to know the status of the track section (free or occupied).
Track circuits contributes also for the vehicle’s speed control, since the electrical signals used for train detection can be exchanged between wayside and on-board for the transmission of speed commands. This can be realized through a modulation of the track signal and is known as “coded track circuits”. Perhaps, no single invention in the history of the development of railway transportation has contributed more towards safety and dispatch in that field than the track circuit.

KEYWORDS: Track Circuit, Train Detection, Axle Counter, Automatic Train Protection.

1. INTRODUCTION

Since the birth of railway signalling, train detection has been considered a primary need [1].
For this purpose, railway tracks are divided into blocks of varying length. Each block stands out from the adjacent ones by means of an insulated joint between rails and it permits the detection of the presence of a train. Track circuits operational principle is based on an electrical signal impressed between the two running rails. The presence of a train is detected by the electrical connection between the rails, provided by the wheels and the axles of the train (wheel-to-rail shunting).
However, this is not the only function that track circuits perform in a railway signalling system because the detection information is used also to control train speed and ensure safe operation, by means of the transmission of speed commands to wayside signaling devices and to the trains [2]. A common operational scenario can summarize the track circuit operation: if a train A attempts to approach too close to the rear of the next train B, the locations information provided by the track circuits is used to command a speed reduction or a trip of the train A, avoiding a possible collision.
The occupancy information of a block is used to control the operation of all trains nearby the occupied area.
When a train is detected on a block, it cause a *stop* command for the block immediately behind the train. Depending upon the block lengths, the line speeds involved, and the number of available speed commands, the second block behind the train may have a command speed between zero and full line speed. The third block behind the train may have a commanded speed greater than or equal to the second block, and so on. In all cases, the blocks behind a train are signaled so that a train entering a block gets the sufficient braking distance [3] to enter the block at a speed not greater than the commanded speed. In the case of a zero-speed command, the train must be able to stop before approaching the end of the block.

2. THE DC TRACK CIRCUIT

The basic DC track circuit was invented by Dr. William Robinson and first used in a railway application in 1872 [4] [5].
The track circuit consists in a block section defined at each edge by insulated joints on the rails. The insulated joints provide electrical insulation between a track circuit and the adjacent tracks. The signal source (in this case a battery) is connected to the rails at one edge of the block section, while the receiver (a relay) is connected to the other edge.

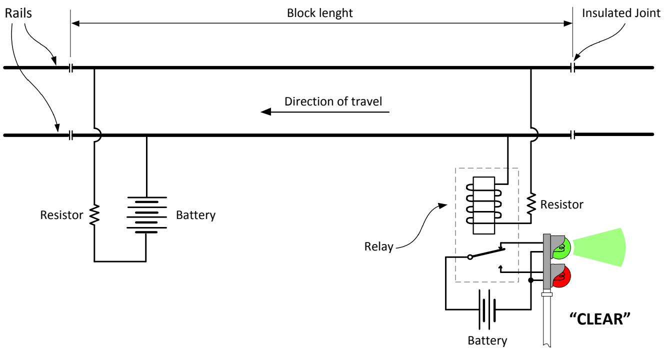

Figure 1: Unoccupied block

When no train is present, the track circuit is *unoccupied*, and the direct current supplied by the battery is transmitted by the running rails to the relay and energizes it or “picks it up”

(APPENDIX A:). When the relay is energized, the green signal light is turned on (Figure 1).
When a train approaches the block, its wheels and axles connect the two running rails together shorting the battery and thereby reducing to zero the current through the relay. This causes the relay to "drop" (Figure 2), turning off the green signal light and turning on the red light to indicate that the block is occupied by a train. A series resistor with the battery protects it by limiting the current that it must provide when a train is present.

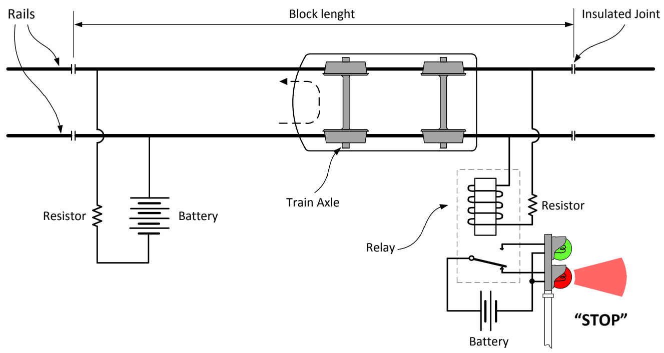

Figure 2: Occupied block

The track circuit shown here has been simplified for the illustration purpose. In practical application [6], the relay would have several sets of contacts connected in combination with the contacts of other relays belonging to nearby track circuits to form logic circuits for the control of the signaling devices.
Even in the simple form shown in Figure 2, it can be noticed that the breaking of any conductor or the loss of power in the circuit will cause either a red signal or no signal at all to be displayed. A red or "dark" signal must be always interpreted as a stop command. To put it another way, all signaling systems are designed so that a green signal (meaning proceed) is presented only when the track circuits provide positive information that it is safe to do so.
The double-rail DC track circuit is susceptible to interference when the running rails are used as the return for DC electric propulsion current. Indeed they are generally installed only in non-electrified sections, and only where there is no concern with stray currents circulating in the earth or in the rails. The main modern application of the double-rail DC track circuit is in railway with diesel-powered locomotives.

3. THE AC TRACK CIRCUIT

The AC track circuit is energized by an alternating electrical current with a frequency of 83.5Hz [7], to avoid interference from the 50Hz traction current. Except for the type of current and apparatus used, the AC track circuit is similar in operation to the DC track circuit described above. Its principal advantage is that it is immune to interference from stray currents, so that it can be used on electrified tracks.

Figure 3 shows a simple AC track circuit. Simirarly to the DC track circuit, the AC track circuit consists in a block section. The AC signal source (Transmitter in Figure 3) is connected to the rails at one edge of the track circuit while the receiver is connected to the opposite edge. A band-pass filter and a rectifier are used to extract a DC signal from the AC track circuit current, for the operation of the track relay. Unless the use of AC signal, the general principle of operation is the same.

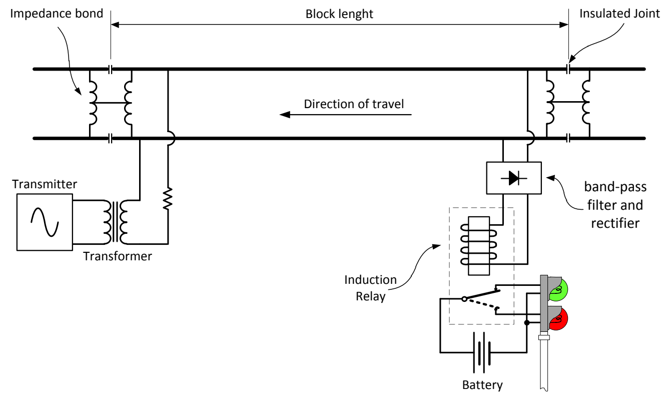

Figure 3: AC track circuit

In addition to the signal source and the receiver, the AC track circuit contains a pair of impedance bonds for each pair of insulated joints. An impedance bond is a center-tapped inductance which is connected across the rails on both sides of the insulated joints. The center taps of the pair of impedance bonds are connected together as shown. The purpose of the impedance bonds is to provide continuity between the track circuits for the DC propulsion power and to distribute the propulsion current between the two running rails. The impedance bonds do this while still maintaining a relatively high impedance at the signaling frequencies between the two rails and between adjacent track circuits (For further details refer to APPENDIX B:).
When no train is present, the alternating current supplied by the transmitter at the left side of the diagram in Figure 3, is transmitted by the running rails to the relay and "picks it up". The energized relay turns on the green signal light, exactly as in a DC track circuit. The wheels and the axles of a train entering the track circuit connect the two running rails together and the current through the relay is reduced, causing the relay to "drop". This connects the bottom set or relay contacts, turning off the green light and turning on the red light to show that the block is occupied.
The resistor in series with the transformer (at the left in the diagram) protects the transformer by limiting the current that it must provide when a train is present.

1.1 High Frequency Track Circuit

Some AC track circuits use an alternating electrical current at a frequency in the range of hundreds or thousands of hertz. Because this frequency range corresponds roughly to the

spectrum of audible sound, such circuits are sometimes called audio frequency track circuits (AFTC) [8].
High-frequency track circuits (HFCT) eliminate the need for insulated joints in the running rails [9]. Because insulated joints are expensive to install and to maintain, eliminating them leads to a significant cost reduction. Eliminating insulated joints also allows the track circuit to operate with the continuous welded rails being used in some newer installations.
Figure 4 shows a simple high-frequency AC track circuit. Since no insulated joints are present in the running rails, the edges of the block are established by special transformers connected to the rails. The transformer winding attached to the rails is usually a single turn of heavy copper bar stock. The transformer core is often a toroid. The other transformer winding is tuned to resonate at the operating frequency by a capacitor. The transmitter is the AC signal source and provides electrical energy at the operating frequency in the audiofrequency range.

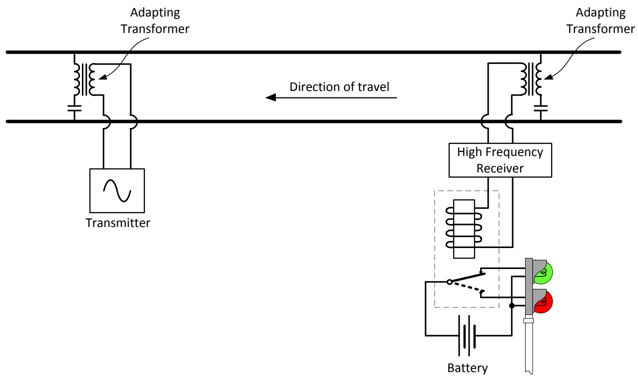

Figure 4: High-Frequency AC track circuit

The receiver in this case is not simply a relay, but an electronic circuit which responds to the electrical signal provided by the transmitter, and usually includes a tuned filter, rectifier, and amplifier for the signal frequency. Electrically, the track circuit zone inside the rail-to-rail shorts looks like two tuned LC circuits in parallel, with the inductance of the enclosed section of track in between them in series. The capacitors are adjusted so that the enclosed section of track is tuned to the track circuit frequency.
When no train is on the track, the signal from the transmitter is received and detected at the receiver, and it is used to keep the track relay energized and the green signal light turned on. When a train approaches the track circuit it shunts the track circuit and, depending on the positions of the wheels, either de-tunes the circuit or shorts the transmitter or receiver (or both). Any of these cause the track relay to be de-energized and relay to drop, turning off the green light and turning on the red light.
The circuit illustrated in Figure 4 is highly simplified, but in practice it is necessary to accommodate the adjacent track circuits on either side. Rather than installing two separate transformers for each track circuit, a second resonant winding can be included in each transformer or a heavy primary winding can be passed through more than one transformer core. Thus, a single transformer assembly is used at the boundary between adjacent track circuits and serves each. Although part of the same transformer assembly, the resonant windings are effectively isolated from each other because they are tuned to and operate on different frequencies.

4. AXLE COUNTER SYSTEM

All of the track circuits described up to this point operate following the closed-circuit principle. Any disruption of the circuit by a train passing along the rails or by power or component failure, “opens” the circuit and causes a stop indication to be displayed by the signal system.
An alternative approach to track circuit design uses a “check-in/check-out” logic. Simply stated, this circuit is based on the principle that once a train is detected or “checked in” to a block, it is assumed to be there until it is “checked out” by being detected in an adjacent block. The presence of a train may be detected only intermittently at the time when it enters a new block. Axle counters are installed at each edge of the section of track (Figure 5); when the number of axles counted at the entrance to the section is the same as the number of axles counted at its exit, that means the train has passed through the section.

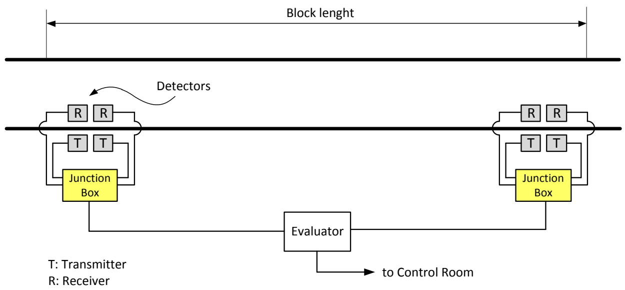

Figure 5: Schematic of a railway Axle Counter system

A detection point comprises two independent couple of detectors, therefore the device can detect the direction of a train by the order in which the detectors are passed. As the train passes a similar counting head at the end of the section, the counter decrements. If the net count is evaluated as zero, the section is presumed to be clear for a second train [10].
The detector senses the wheels by evaluating the changes in the magnetic coupling between the coils placed at each rail side (Figure 6). The system consists of:

- A sensor coils for train wheels detection;
- An electronic unit (electronic junction box) for signal conditioning and counting of the wheels;
- An evaluator unit which compares the number of the wheels entering the rail section and the wheels exiting the section.

The comparison result states the occupation status (section clear or occupied).

Axle counter detector makes use of electromagnetic flux linkage between two coils mounted on either side of the rail, to detect the passage of the wheels.
The magnetic flux generated by the transmitting coil flows through the path with lower reluctance. In the presence of the wheel, the magnetic path is shaped through the wheel and rail, causing less flux flow in the receiving coil and hence lower induced voltage in the receiver.

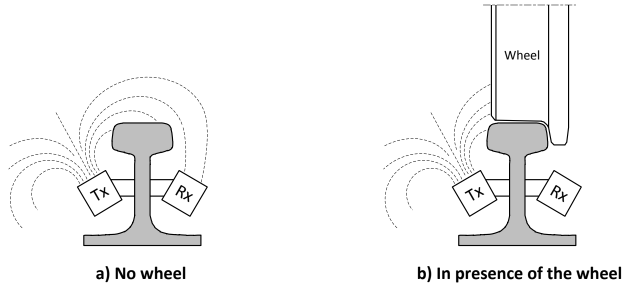

Figure 6: Distribution of magnetic flux

In order to detect the passage of a wheel, the induced voltage in the receiving coil is continuously monitored and its changes beyond some predefined threshold is interpreted as existence or absence of a wheel. In other words, the wheel detector detects the wheel when the amplitude of induced voltage in the receiving coil is less than a threshold level.
Axle Counter has some operational disadvantages, like the effects of a temporary loss of power to the signal system.
With conventional track circuits, this eventuality causes all track circuits to indicate occupancy, but when the signal power is restored, the real occupancy situation is still indicated. With the Axle Counter system, the loss of signal power may destroy the "memory" circuits in charge of "remembering" that a train has entered a block. Thus, when the signal power is restored, the information on block sections which are occupied may have been lost. In this case the identity and location of each train in the affected portion of the system must be established before the entire transit system can be operated again safely.
In a small transit system the identification and location of each train may not be difficult to establish. However, in a large complex system even a short-term interruption of a portion of the system can create a bottleneck which makes the full system restoring very difficult. Thus, axle counter systems do not find application as the primary train detection system in rail rapid transit systems.
Axle counters are used in some cases where track circuits are hard or impossible to operate (e.g., where metal sleepers are provided, making track circuit operation impossible without re-installing the track, or where conditions are such that there is too much electrical noise and conductivity problems that make track circuits an unsuitable solution).

5. SPEED COMMAND AND CONTROL

It is important to understand the principle of closed-loop control before proceeding to a discussion of how speed commands are transmitted and received. A closed-loop control system, also known as feedback control system, is a control system in which an information feedback of the status of the system (or its response to command inputs) is used to modify the control of the system [11] [12].
The basic purpose of closed-loop control is to assure continuity of control by confirming that command inputs have been received and that the commanded system status has been achieved.
The alternative to closed-loop control is open-loop control, where commands are transmitted to the controlled element without any feedback or acknowledgment that the command signal has been received and interpreted properly.
Thus, a closed-loop system, in contrast to an open-loop system, is characterized by continuous control and self-adjusting commands conditioned by observation of system response. The traditional wayside signaling of rail rapid transit is an open-loop system, so is a manually operated train with cab signals, although the automatic overspeed and stop enforcing mechanisms of cab signals represent the beginning of a closed-loop system.
ATP systems are true closed-loop systems. Feedback is used to monitor the response to propulsion and braking commands [3] and regulate the system performances on a continuous real-time basis. The speed control technology for transit vehicles is based on track circuits. The signals used for train detection can also be used for the transmission of speed commands to wayside signaling devices and to the trains. Two general methods are used for the transmission of such commands:

1) **Coded Track Circuit**: used with DC or AC track circuit, in which the signal is turned on and off at a specific rate, and this is interpreted as a speed command for the on-board system.
2) **Binary Coded Track Circuit**: used with AFTC, in which the frequency of the track signal is changed from one to the other of two discrete frequencies.

With either method, wayside or on-board equipments on the wayside sense the signals in the rails and decode the speed command.

5.1 Coded Track Circuits

This technique is applicable to either DC or AC track circuits. The track circuit signal is switched on and off (modulated) at a rate which is related to the speed command [13]. The switching rates are in the range from about 50 to 500 times per minute.
In a DC track circuit, the direct current applied to the running rails at one edge of the track circuit is simply turned on and off at the desired rate. The wayside equipment at the other edge of the track circuit receives and decodes the signals. A code-following track relay is used in the track circuit and continuously codes when the circuit is not occupied. The relay is energized when the current is allowed to flow and is deenergized or when the current stops. The decoding equipment is actuated by the contacts of the code-following

relay. When a given code (rate of transmission) is received, a particular relay in the decoding equipment is energized and remains energized as long as that code is being received. The relay, in turn, controls the appropriate wayside signal. When another code is received, another relay is energized as long as that code is being received. When a train approaches the track circuit, the code-following relay is deenergized, and this fact is used to indicate the presence of a train.

In automatic signal territory, the controls for signals are accomplished by the use of various code rates in the coded track circuit. The three standard code rates are 75, 120 and 180 cycles per minute. The 75 code is used for the caution signal. The 120 code is used for the caution aspect. The 180 code is used for the clear aspect. It is understood that the absence of code will result in a stop aspect.

In AC track circuits, either high-frequency or audio-frequency, the AC signal is turned on and off at a selected rate, in other words the high-frequency carrier is OOK modulated [15] [16] with the code that need to be transmitted.

Since the switching rates for the coded signals are so much slower (l-3 per second) than the frequencies of the AC signals applied to the track circuit (50-150 per second), many cycles of the AC signal occur during the time that the code signal is switched on. The coded track signal can be received by wayside equipment at the far end of the track circuit and used to control wayside signals or it can be received on board a train and used to control the speed of the train.

The presence of a train stops the operation of the code-following relay and indicates occupancy of the track circuit. The coded track signals are received on board by a pair of coils mounted near the front of the leading car, just a few inches above each of the two running rails and in front of the first set of wheels and axle (Figure 7).

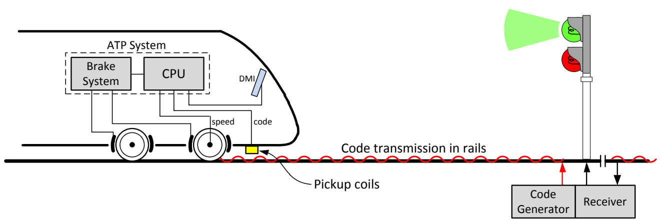

Figure 7: Coded track circuit

The magnetic field from the electric current carried in the rails produces a signal in these coils (sometimes called antennas), and this signal is processed or decoded to determine the switching rate and hence the speed command.

The decoded speed command is used in automatic systems to control the speed of the train. In semiautomatic systems, the decoded speed command is displayed to the train operator (Figure 8), who needs to regulate train speed manually.

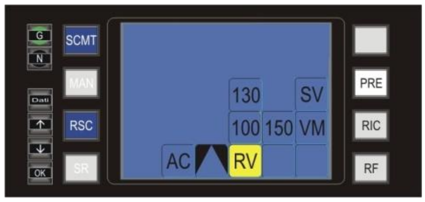

Figure 8: Ansaldo DMI with coded track circuit activated

5.2 Binary Coded Track Circuits

This technique is sometimes used with audio-frequency AC track circuits. Instead of turning the track circuit signal on and off, the frequency of the track signal is changed from one to the other of two discrete frequencies, producing a binary FSK modulated signal [14] [15] [17].

It is particularly adaptable to digital systems in which one frequency corresponds to the transmission of a “1” and the other frequency corresponds to the transmission of a “0”. The track circuit receiver responds to both of the signaling frequencies that are used. When a train approaches the track circuit, the amplitude of the signals at the track circuit receiver is reduced below some threshold and this information is used as an indication of the presence of the train.

6. CONCLUSION

Already at an early stage it was found necessary to be able to ensure, automatically and absolutely reliably, that a track section was free from trains. Track circuit was the first to be developed and it is the fundamental method of train detection, and while there has been experimentation with other methods over the years it remains the more reliable. As described there are several types of track circuits, but the detection principle is similar for each.

Perhaps, no single invention in the history of the development of railway transportation has contributed more towards safety and dispatch in that field than the track circuit. By this invention, simple in itself, the foundation has been obtained for the development of practically every one of the intricate systems of railway block signaling in use today whrein the train is under all conditions continuously active in maintaining its own protection.

NOMENCLATURE

AC	Alternating Current
AFCT	Audio Frequency Track Circuits
ATC	Automatic Train Control
ATP	Automatic Train Protection
DC	Direct Current
DMI	Driver Machine Interface
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
FSK	Frequency Shift Key
HFTC	High Frequency Track Circuits
OOK	On Off Key

REFERENCES

[1] Williams A., Kichenside G., "Two Centuries of Railway Signalling", Ian Allan, January 2009.

[2] Duffy, Michael C., "Electric Railways 1880-1990", Institute of Engineering and Technology, 2003.

[3] European Railways, "Description of the brake curve calculation", Ref. EEIG-ERTMS: 97E881 ver 5D, Jul 2001.

[4] Robinson W., "Improvement in Electric-Signaling Apparatus for Railroad", U.S. Patent US130661A, August 1872.

[5] American Railway Association, "The Invention of the track circuit : the history of Dr. William Robinson's invention of the track circuit, the fundamental unit which made possible our present automatic block signaling and interlocking systems", New York 1922.

[6] Railway Group Standards, "DC Track Circuits", GKRC0755 Iss2, Dec 1998.

[7] Railway Group Standards, "83 1/3 Hz A.C. Track Circuits", GKRC0758 Iss1, Dec 1998.

[8] Railway Group Standards, "TI.21 Audio Frequency Track Circuits", GKRC0761 Iss 1Use, Jun 1996.

[9] Hans Fricke, Jurgen Kiess, Lutz Schulmeyer, "Decoupling arrangement for non-insulated AC track circuits in railway systems", U.S. Patent US4373691A, Dicember 1980.

[10] Hofstetter Ernst, Haas Kurt, "Axle counter for railroad installations", U.S. Patent US3015725A, June 1960

[11] Wright, N. & A. Hamilton, "ATP – The Train Operator's Perspective", IRSE, 16 January 2002.

[12] Ning, Bin, "Advanced Train Control Systems", WIT Press, June 2010.

[13] Harry C. Nagel, "Pulse code system for railroad track circuits", U.S. Patent US4619425A, July 1981.

[14] Anthony G. Ehrlich, "Single-element coded alternating current railway track circuit having double-element, phase-selective capability", U.S. Patent US5219426A, February 1992.

[15] Emmerson, A. (Ed.), "Railway Telecommunications", IRSE, 2004.

[16] Proakis, Salehi, "Communication Systems Engineering (2nd Edition)", Prentice Hall, August 2001.

[17] Leon W. Couch, "Digital & Analog Communication Systems", Prentice Hall, January 2012.

[18] Solomon, Brian, "Railroad signalling", Voyageur Press, 2003.

[19] Olivier Leveque, "ETCS Implementation Handbook", UIC, May 2008.

[20] European Railway Agency, "ERTMS/ETCS System Requirements Specification", USIGN SUBSET-026, April 2012.

BIOGRAPHY

Jodi Scalise got in July 2013 his Master's degree in Electronic Engineering at University of Florence. (Italy) He's a curious, proactive and willing to learn engineer. He has worked at ECM S.p.A. in Pistoia, as electronic designer and validation engineer since the beginning of 2011.
He has been involved in test and validation of many ETCS subsystems projects. In particular, he is specialized in track circuits technologies, Eurobalise technologies and odometer subsystems. He collaborates with railwaysignalling.eu since Semptember 2014.

APPENDIX A: FAIL-SAFE RAILWAY RELAYS

The terms "pick up" and "drop" refer to the position of the special "fail-safe" relays used for train detection. These relays are constructed from specifications approved by the Association of American Railroads and are designed so that their normally open "front" contacts will be closed only when sufficient electrical energy is being supplied to the coil. One or both of the normally open contact members are made of carbon or carbon impregnated with silver, which cannot be welded. The relays use gravity rather than spring return and are mounted vertically so that the relay armature, to which the contacts are attached, is returned to the dropped position when the current through the coil is reduced below some critical value. The failure rate of these relays for the mode in which the normally open contacts would be closed with no power applied to the relay coil is so low that for all practical purposes it is considered to be zero.

APPENDIX B: IMPEDANCE BONDS

Impedance bonds used for AC track circuits consist of two low-resistance windings wound in opposite directions on a laminated iron core. Each winding is connected across the rails on either side of the track, and centre taps from each winding are connected together. With DC traction, under normal circumstances equal currents flow in each half of each winding and if the traction currents are evenly distributed across the two rails, there is no resultant flux in the iron core. In this state, when the core is not magnetized, it presents a path of high impedance to the track circuit current. In the case of an imbalance, the core would be magnetized to saturation and the track circuit current would no longer be faced with a high-impedance path; therefore, an air gap is introduced in the magnetic circuit to prevent saturation, and the impedance bond presents high impedance to the track circuit current in all cases up to about 20% traction current imbalance. With AC traction, when the traction currents are unbalanced, the half coil that carries more current induces an e.m.f. in the opposite half coil that tends to equalize the current. So air gaps are not generally necessary for AC traction. The impedance of the bond to the signalling current can be further increased by adding a secondary coil and a capacitor across it, in what is known as a resonated impedance bond Figure 9.

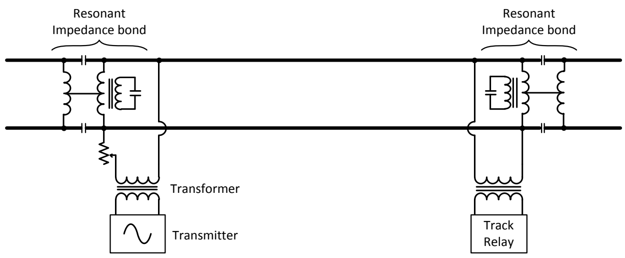

Figure 9: Track circuit with resonant impedance bond

The secondary coil steps up the voltage and allows the use of a smaller capacitor than would otherwise be required.
Auto-coupled impedance bonds are a modification of the resonated impedance bond idea (Figure 10).
Here the winding across the rails in the track circuit zone forms one part of the winding of an auto-transformer, the other part having the capacitor in series. On one side of the track circuit, the other part of the auto-transformer is

connected to the supply thereby being stepped down for the track circuit current, and the auto-transformer winding on the other side of the track circuit is connected to the track relay such that the track circuit current is stepped up to operate the relay. Thus, the current flowing in the bonds is usefully employed in operating the relay.

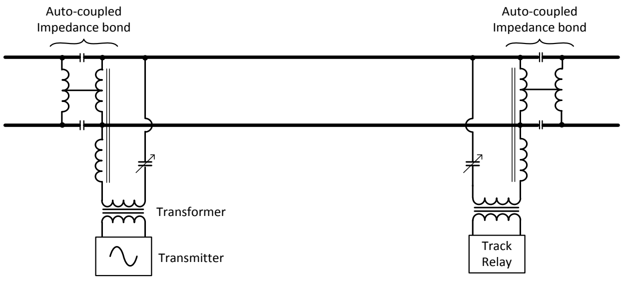

Figure 10: Track circuit with auto-coupled impedance bond

APPENDIX C: MULTI-ASPECT SIGNALS

The basic, two-aspect, red/green signal is suitable for low speed operations but for anything over about 50 km/h the driver of a train needs a red signal warning ahead to give him room to stop. This led to the idea of caution signals (originally called "distant" signals when they were mechanically operated semaphore arms) placed far enough back from the signal, protecting the entrance to the block to give the driver a warning and a safe braking distance.
Since this concept has been developed for track circuited signalling, the caution signal was provided a block further back from the stop signal.
Each signal would now show a red, yellow or green aspect anda multi-aspect signal [18] [19].

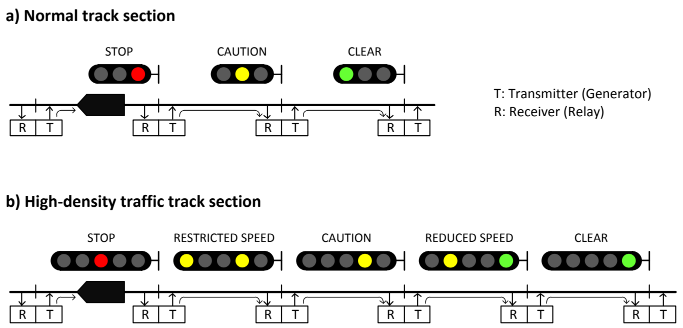

Figure 11: Schematic of multi-aspect signalled route

As shown in Figure 11, there are three main signal aspects:

- **Red**: stop immediately before entering the next track section occupied by an ahead train;
- **Yellow**: proceed with caution at a speed no greater than 40km/h (may vary) as far as the signal;
- **Green**: the next track section is clear and the train can enter that section at the maximum speed.

In heavily used section, two other signal aspects are olso used, two yellow light (restricted speed) and one yellow and one green light (reduced speed) [18] [19] [20].
Signals showed in Figure 11 are not universal, and different railroads may use different signal types or arrangements of colors.