Future challenges to wheel detection and axle counting

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Axle counting systems with inductive wheel sensors have established themselves with many railway operators worldwide as reliable and cost-effective track vacancy detection systems. Progress achieved in the development of the operating principles, manufacturing processes and materials, and the decades of practical experience, are the basis for the steadily growing number of applications and solutions. The development of ever more advanced and diverse vehicles and the increase in electromagnetic emissions and speed, however, remain a major challenge for safe and reliable wheel detection. This article, which is part 1 of a comprehensive survey, provides an overview of modern wheel sensor systems. Part 2 will deal with the state of the art in axle counting.

1 Wheel detection

Even in the early days of the railway in the 19th century, wheel detection had been an urgent desire of railway engineers concerned about signalling safety. Their use as a switching device for train-controlled level crossing systems, track vacancy detection systems, automatic switching of signals to stop aspect or automatic route release, and also as on/off switching devices for a wide range of track equipment (e. g. measurement systems, gates, washing plants, weighbridges) significantly increased their importance over time and with it the requirements regarding availability and safety.

The devices developed to this effect are still known as track switches or rail contacts due to their intermittent principle of operation.

In the past no special components for evaluation of signals were necessary because the switch contacts integrated in the track switching system were usually directly looped into the relay circuits. That is not the case where modern wheel sensors are concerned. Here analogue signals form the output signal, which requires interpretation by an evaluation component (such as an evaluation board) (Figure 1).

2 The operating principles of track switching equipment [1]

2.1 Mechanically operated rail contacts

In general, these consist of a contact device mounted on the inside of the foot of rail, which is actuated by the wheel flange via a lever. Due to their interference susceptibility they were replaced in Europe at the end of the 19th century by hydraulic rail contacts. They can still be found in non-signalling applications, such as warning systems for work gangs.

2.2 Hydraulically operated rail contacts

The not very widespread class of hydraulic rail contacts was usually actuated by the deflection of the rail caused by the axle load. Cylinders – at first filled with mercury, and then with hydraulic oil – operated a contact set. As early as 1920, these hydraulic track switches were replaced in Germany by pneumatically operated switching elements.

2.3 Pneumatically operated rail contacts

Due to their long-term use several types have emerged, which differ quite widely in terms of operation and construction. In essence, the force exerted on a piston led to pressure differences in airtight chambers which, for example via a membrane, actuated a contact device. To achieve a reasonably acceptable availability this type of track switch required specific axle loads or minimum speeds, which, naturally, limited their application. So, from the 1950s on they were progressively replaced by magnetic contacts.

2.4 Magnetically operated rail contacts

The first contactless switching devices were employed in the middle of the last century. The rail contacts known as axle counting magnets or pulse generators

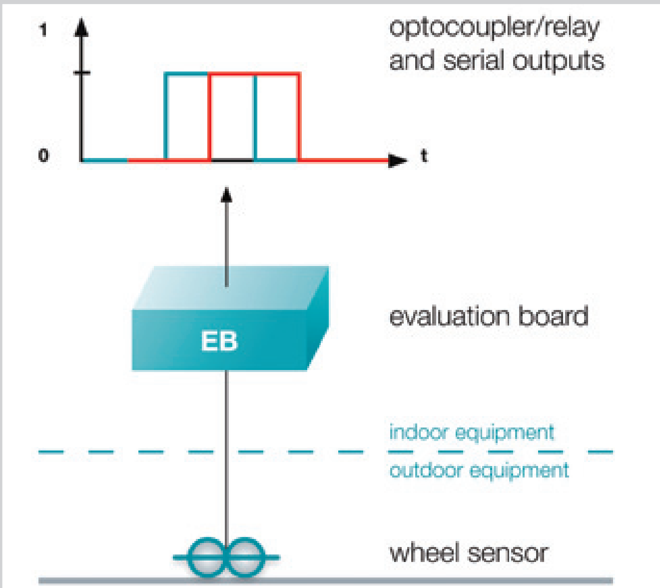

Figure 1: Components for wheel detection

feature a permanent magnet system, to which magnet-operated electrical contacts are exposed. The effect of the iron of the wheel flange triggers a contact actuation due to the change of the magnetic field. Magnet-operated rail contacts of different types and operating principles can still be found on many railways in the world. In Central Europe, they are increasingly being replaced by inductive devices as they are sensitive to external magnetic fields.

2.5 Inductive operating principles

In parallel with the development of magnetically operated track switches, contactless switches based on the transformer principle were launched in the market. A primary coil generates an AC magnetic field in an iron core with at least one air-gap in the direction of the head of rail. A wheel flange passing over the air-gap changes the magnetic flux and consequently the induction in a secondary coil, preferably designed as a differential coil. This operating principle was later improved by using ferrite magnets and increasing operating frequencies.

During the same period, devices were designed that operate according to the magneto-dynamic principle. The operating principle of the rail contacts designated as magnetic pulse generator is based on a permanent magnet system with a soft iron core. The flux changes caused by the passing wheel flanges induce measurable voltages in the coils placed in the area of the magnetic flux. This operating principle requires a certain speed, which, however, by means of continuous improvement of the circuits, was reduced to practically zero.

Widely used are rail contacts with a transmitter coil on one side of the rail and a receiver coil on the other. The wheel or tyre affects the inductive coupling between transmitter and receiver. The devices are mostly designed as double sensors and are often used as counting heads for axle counters.

In the 1970s, the emergence of integrated circuits strongly influenced the operating principle of rail contacts. Simultaneously with enormous advances in the field of industrial electronics, the operating principle of the inductive proximity switch took its first steps. At first, so-called head of rail switches were mounted into a vertical bore in the head of the rail in order to allow detection of the wheel treads. Subsequently, a model prevailed which was mounted laterally to the inside face of a rail and whose upward placed coils detected the presence of the wheel flange.

Track switches based on this fundamental principle are today being used as wheel sensors of different types and varying modes of operation and will be the basis for safe wheel detection with maximum availability in the future.

Figure 2: RSR 123 under hail

2.6 Other operating principles

The limits to the use of inductive track switches imposed by the laws of physics as well as the extremely complex technological hurdles to design a reliable and safe sensor based on these operating principles are always prompting the development of wheel sensors based on other principles of physics. Examples include microwave technology, piezoelectrics, fibre optics or sound technology. However, none of these approaches has so far led to a licensable system ready for serial production.

3 State of the art

The state of the art of wheel sensor systems is geared towards the requirements users want developers to provide for. Almost all of the systems described above can still be found, even today, in many rail networks. This article endeavours to outline which technologies will play a crucial role in the future.

3.1 Challenges

3.1.1 Mechanical loads (vibration and shock)

Shocks are mainly caused by flats on the running surface of the wheels, while vibrations are generally caused by short pitch corrugation of the rail surface. EN 50125-3 defines the values for mechanical shock and vibrations. In practice, significantly higher loads may apply. Less important, but defined by rail operators in some specifications, are minimum loads the sensors are required to withstand without so much as moving.

3.1.2 Climatic constraints (ambient temperature, humidity, snow)

The extreme temperature range from −40 to +85 °C (reaching up to −60 °C in Nordic countries) is covered by most electronic components, but is a major challenge for the development of frequency-stable and quality coils. The fact that coils are still made of copper conductors which need to be embedded into a sealing compound in order to be protected against humidity entails the following problems: Increased temperature implies higher copper resistance and reduces coil quality, which is also influenced by the dielectric loss factor of the sealing compound between the coil windings. The relationship between dielectric loss factor and temperature is not linear and normally increases distinctly after +60° C. The magnetic fields generated in practice by inductive sensors and ranging from a few kHz up to several MHz do not, as a rule, cause interference in case of humidity, snow and frost. However, high operating frequencies also generate electrical fields, which respond to the capacitive influence of water. It is therefore necessary to compensate this equipment against the propagation of electrical fields influenced by water or ice.

The requirement for compliance with the highest protection class IP 68 according to EN 60529 becomes a technological challenge for modern electronic wheel sensors, particularly with regard to use and/or life cycles at the track, because the sensors must ensure reliable operation even under extreme climate conditions (Figure 2, 3, 4).

3.1.3 Rail temperature, rack currents

The head of rail is very much exposed to the sensor coils. At a rail temperature of –40 up to +100° C (additional heating of the rail due to linear eddy current brake) both permeability and conductivity of the iron change considerably. This leads to a drift in the sensor coil and causes, as temperature rises, an increase of eddy current losses and, simultaneously, a decrease in hysteresis losses due to declining permeability of the material. Neither process is linear in regard to the given operating frequency.

Furthermore, the rail material is affected by permeability changes due to track currents. Track return currents generate a magnetic field, which also magnetizes the surface of the rail material. As a result permeability of the head of rail material is reduced and, consequently, the hysteresis losses registered by the sensor coil decrease. AC traction is also different from DC traction. Short-circuits up to 40 kA in the overhead contact line or transients due to discharge into atmosphere can cause magnetic saturation of the rail material and thereby suppress hysteresis losses altogether.

3.1.4 Magnetic field generated by track return currents

Track return currents generate a magnetic field that is disposed concentrically around the rail, wherefore the sensor coil is fully exposed to the field. If the sensor coil has a ferrite core, the magnetic field may cause its saturation. Short-circuits in the overhead contact line and currents from discharges into the atmosphere entail similar effects.

3.1.5 Traction current commutation

The sparks which can often be seen at quite a distance around the pantographs of the vehicles or contact problems between rail and wheels cause changes in the level of the return current within a broad range of frequencies. The resulting magnetic fields induce voltages into the sensor coil, which have to be compensated.

3.1.6 Electromagnetic rail brakes, eddy current brakes

These braking elements have several effects on wheel sensors. On one hand, the metal and coil volume of the brake, which reaches laterally over the head of rail into the effective range of the sensor, causes a partial damping of the sensor system, which must not trigger the sensor as if it were a wheel flange. On the other hand, both types of brakes, especially the eddy current brake, generate an enormous magnetic field, which in turn has two different effects. The magnetic field permeating the steel of the head of rail will cause its magnetic saturation. Effects are similar to those described in subsection 3.1.3 and the leakage magnetic field also reaches the sensor, which has to cope with it without disturbance. Effects are similar to those described in subsection 3.1.4.

3.1.7 Interfering magnetic fields generated by vehicles (inverters, coils, transformers)

Low-loss performance inverters require high switching frequencies and steep switching flanks. Therefore, interfering magnetic fields with large bandwidth and frequencies ranging up to several MHz are to be expected under the vehicles. Where an interfering magnetic field collides directly with the operating frequency of the sensor, effects are especially drastic.

3.1.8 Vehicle geometries (effective ranges)

All wheel sensors have defined and more or less clearly identifiable effective ranges. Consequently, sensitivity with regard to approaching iron masses differs accordingly.

Especially in the case of trams, subways and suburban trains (light rail vehicles), optimized bogie geometries in combination with electromagnetic rail brakes often cause problems for safe and readily available wheel detection. In the case of modern vehicles with underfloor mounted equipment in particular, the wheel flange signal can hardly be distinguished anymore from other interfering iron masses, such as the electromagnetic rail brake. This is further compounded by smaller wheel diameters in combination with small distances between axles.

The wheel-axle-rail-sleeper geometry can also be looked at as a conductor loop, which is exposed to part of the magnetic field generated by the sensor. If the resonant frequency range of the loop is similar to the operating frequency of the sensor, the sensor system may be affected. At Frauscher, this type of interference is designated as “parasitic absorption”.

3.1.9 Installation and mounting

The requirements regarding installation and mounting are the results of historically evolved regulations of the rail operators, which factor applications and structural conditions regarding rail profile, superstructures and track embedding (for example, in roads).

Meanwhile, wheel sensors are being used in large quantities. Their cost-effectiveness is, therefore, also geared towards fast mounting and dismounting. Here, web of rail mounting with drilling has mostly been replaced by clamping. Moreover, short mounting periods with inherently shorter permanence of work gangs at the rail are a clear safety gain.

For example, when used as switching device for warning systems for work gangs, in addition to mounting and commissioning times (adjustment of sensor system), the weight of sensors and rail claws also plays a decisive role.

Furthermore, the mounting technique is expected to be highly flexible. Mounting in the space between sleepers or on a sleeper, in the immediate vicinity of guide rails, in grooved rails beneath the tram track or fixed track systems are, for instance, current requirements for such systems.

3.2 Highly available wheel sensors

Among the operating principles described in section 2, inductive wheel sensor technology has become widely accepted. Specific properties allowing trouble-free masking out of known interferences, while correctly sensing the wheels, are required.

Figure 3: RSR 180 under snow

Generally and for the purpose of failure detection, a wheel sensor comprises two sensor systems that operate independently. The redundancy affords other functionalities of the wheel sensor system, resulting from the temporal context and the intensity of the interference.

Although in all cases using this operating principle at least one coil through which AC current is passing acts as core element, on closer examination it is necessary to further differentiate between the following methods:

- Eddy current and hysteresis method: The AC magnetic field radiating from the sensor coil causes eddy current and hysteresis losses in ferromagnetic materials (here: wheel flange) that are exposed to it. These losses reflect back on the sensor coil and reduce the quality of its oscillating circuit.
- Field deflection method: The magnetic field generated by a coil supplied with alternating current is deflected by existing ferromagnetic materials in such a way that induction in a close-by receiver coil changes. This deflection can increase or decrease.
- Inductivity method: The inductivity of a sensor coil changes due to the influence of ferromagnetic materials in its vicinity. The influence of the material depends on the operating frequency.

Wheel sensor type RSR 122 by Frauscher Sensortechnik GmbH, for example, operates according to the „eddy current and hysteresis method“ while wheel sensor type RSR 180 operates according to a well-proven combination of „field deflection method“ and „inductivity method“.

The mode of action of the extremely innovative RSR 123 consists of a technology mix combining the three inductive methods described above (V.Mix technology) [2]. The properties of the RSR 123 mark a state of the art which, considering the resistance against interferences as described under 2.1 (see Figure 4), represents an optimal solution (Figure 5).

3.3 Track switches – wheel sensor

A track switch can only send two types of information, i. e. “occupied” or “free”. Further information such as its position with regard to the track, occupation status, evaluation of external interferences or deficient wheel flange formation is not within its scope.

Several decades of experience in the development of inductive sensors have shown that it is practically impossible to meet the challenges stated under 3.1 without an analogue output signal that measures the distance. This becomes especially apparent when wheel sensors are used in an environment affected by undesirable interferences such as extremely busy track sections with multiple traction units (AC and DC), applications under extreme environmental conditions such as industrial facilities located in extreme climate zones or in trams with underfloor mounted equipment.

The Figure 6 shows the signal curve of a typical Frauscher wheel sensor with two independent sensor systems (sys 1 and sys 2) while being traversed by a wheel. The possible overall signal range can be divided into the following ranges:

Figure 4: RSR 122 in sandy location

- Range 1: Sensor correctly mounted on rail, no interference from wheel
- Range 2: Sensor dropped off from rail (signal rises, because the head of rail is outside the effective range).
- Range 3: Sensor damped by wheel
- Range 4: Wire break or defective component

Contrary to a switch limited to "ON" and "OFF" or "High" and "Low" status detection, an analogue sensor, provided a matching intelligent evaluation board, affords a measure of further information.

3.4 Evaluation features

The signal values are provided at the wheel sensor in the form of injected current values, which can be evaluated in the indoor installation over the cable link by an intelligent board, the evaluation board, using different algorithms. To that effect and in addition to the actual useful signals of the wheel sensors, status data of the sensor regarding its safe operation can also be transmitted, such as drop-off detection, proper installation, deficient damping, drift values and faults in the sensor system, thereby allowing the system to dispense with sensitive and expensive trackside electronics. This not only increases the economic efficiency of the installations, but also provides sustained reduction of commissioning and maintenance costs.

The power supply of the analogue signal values affords a number of further evaluations besides the status outputs mentioned above.

In addition to wheel detection proper, modern wheel sensors combined with intelligent evaluation boards are able to also determine wheel diameter, traversing speed, traversing direction, wheel centre above the sensor or the presence e.g. of an electromagnetic rail brake.

Furthermore, the analogue sensor signal allows triggering of the output of the rectangular signal used for counting purposes at freely pre-selectable signal levels, thereby affording detection of wheel running surfaces without wheel flanges or wheel flanges exerting less contact on the head of rail.

It is also possible to derive relatively simple basic information for centralised diagnosis of the sensor system by the indoor installation. The FDS diagnostics system by Frauscher [3] for axle counting system ACS2000 is a typical application of this ability (see Signal+Draht 1+2/2010).

There is already a large number of evaluation boards available for all these data exploration options as well as several hardware platforms, with different versions of software and evaluation algorithms. For example AMC, IMC boards (universal evaluation boards with optocouplers), EIB, AEB boards (CAN interface) or VEB board (safe output of speed).

Thanks to the possibility of customized evaluation options under known conditions or others to be defined, maximum functionality and availability can be achieved for each specific application. This is why Frauscher places particular emphasis on customer-transparent test installations in the preliminary stages, particularly with regard to their interference capability on critical wheel sensor applications. A technical article in Signal+Draht 6/2011 presented the measurement technology developed and implemented to that effect [4].

Furthermore, these evaluation boards can also be differentiated based on their interface to the higher-level application. There are versions including relay interfaces, optocouplers or serial interfaces.

3.5 Modern installation options for wheel sensors

Mounting and installation procedures for wheel sensors at the rail have a major bearing on the practicality, life cycle costs and possible applications of wheel sensor systems.

The state of the art are high-quality, highly available and safe rail claw technologies that can be used for all known railway designs and different rail profiles (grooved rails). The installation of wheel sensors using rail claws that can be mounted easily and quickly without the need for special tools also enables the use of this latest technique of wheel detection as temporary or flexible solutions, e.g. for warning systems for work gangs.

The fact that the cable to the sensor (sensor cable) for the inductive wheel sensors described herein is not part of the mode of action of the sensor further allows flexible customized sensor cable assemblies even after installation.

In future, plug-in cables for sensors will become a global standard. Wheel sen-

Figure 5: Patented V.Mix-Technologie® for highest demands

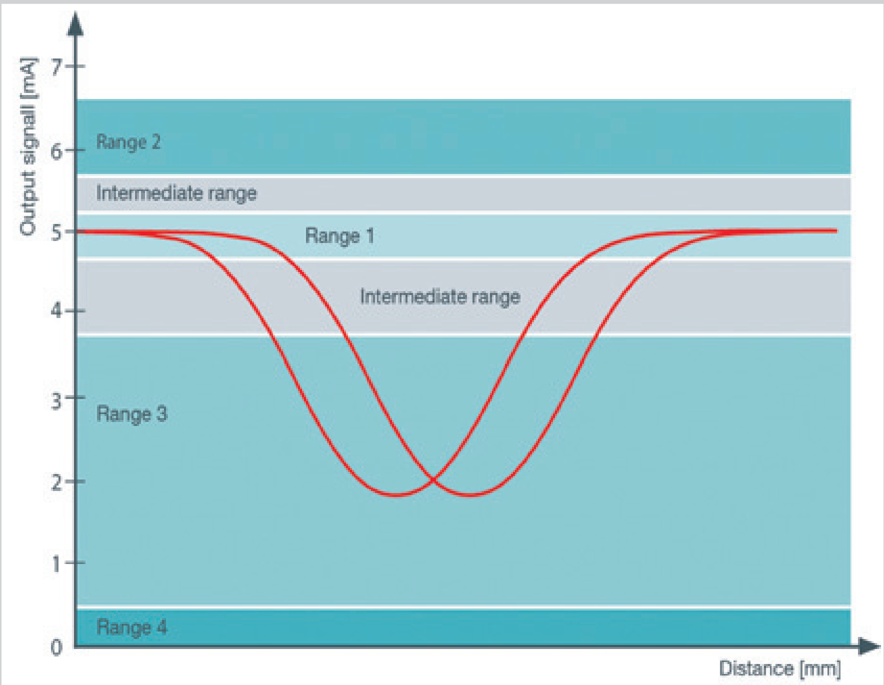

Figure 6: Evaluation example of an analogue signal

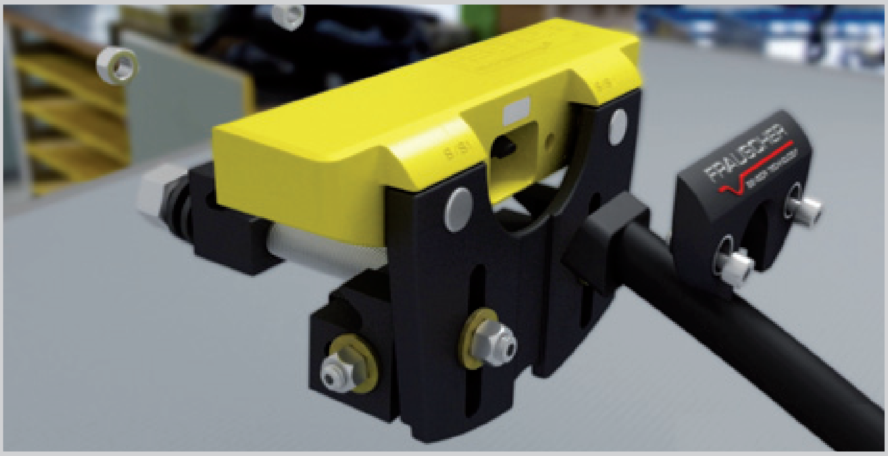

Figure 7: Fast and easy mounting of a sensor using rail claws and plug-in cables

sors RSR 123 and RSR 181 by Frauscher already provide these options with all the advantages for the installation of new signalling systems or for mounting and dismounting during track maintenance work (Figure 7).

4 Wheel detection and its applications

If track switching equipment as part of track vacancy detection systems meets the specification requirements of railway operators for axle counting systems, in theory they could also be used for other safe systems. A classification of such systems as CENELEC SIL 4 systems has increasingly become a global basic requirement, e.g. for axle counting systems.

But only in the form of inductive wheel sensors with analogue output signal and a matching evaluation board will these wheel sensor systems afford the wide range of possible applications both as SIL 4 systems and for systems with graded safety degrees according to CENELEC D, i.e. SIL 0 – SIL 3.

4.1 Track vacancy detection

Axle counting for track vacancy detection has been and still is the most challenging field for track switching equipments. Only inductive wheel sensors made safe axle counting highly available and are increasingly and gradually replacing track vacancy detection with track circuits all over the world.

Over the years, many forms of track vacancy detection have been developed on the basis of axle counters.

4.2 Level crossings

Track switches to activate and/or deactivate level crossings have been around since the early days of track switching equipment. Modern wheel sensor systems meanwhile allow safe on/off switching points for level crossing using just single sensors. The globally available range of configurations and combinations with axle counting circuits is almost endless.

Further development of wheel sensor systems, e.g. to be able to provide speed information safely and cost-effectively, will make these applications even safer, more flexible and more cost-effective.

4.3 Switching applications (triggering)

Modern wheel detection, switching highly available systems in near real time and accurately with high resolution on and off, is nowadays an integral part of many different systems. Examples are trailing messages, hot axle box detectors, flat detection equipment, weighbridges, washing plants, gates, tunnel lights and passenger information systems (Figure 8).

4.4 Measurement applications

As wheel detection with analogue output, in addition to wheel detection proper, using several intelligent algorithms, also provides information about traversing speed, traversing direction, wheel diameter, wheel centre above sensor or the existence of e.g. an electromagnetic rail brake, a large number of other applications based on wheel detection are feasible, being designed or already implemented.

For example, speed control sections can be implemented for speed restriction sections based on speed measurement by inductive wheel sensors. Speed-sensitive passenger information systems also use this option. Wheel centre detection has been implemented in several hot axle box detector systems (HOA). Wheel diameter detection, for example, can be used to optimise the operation of rail brakes.

Within the scope of intelligent axle counting systems with serial interface to integrated electronic signal boxes, this information (especially, speed) can be processed for a wide range of additional functions in the signal box in parallel with track vacancy detection and be used in additional features to the benefit of the customer.

Figure 8: Hot axle box detector system controlled by wheel sensors

5 Perspectives

Future-safe and highly available wheel sensor systems will be based on inductive sensor systems with analogue output signal. Decades of experience of Frauscher Sensortechnik GmbH and over sixty thousand installations worldwide show that in the long term only this technology will be able to meet the challenges arising from the interferences listed in section 3.1. The increasing functional demands are satisfied by different evaluation boards featuring specific software evaluation algorithms. However, tapping the full potential will only be possible if the core elements – sensor and evaluation board – are optimally tuned to each other.

These systems combined with optimised rail claw mounting and plug-in sensor cables meet all future requirements in regard to cost-effectiveness, flexibility and optimal maintainability.

The possibility to transfer complex information that goes beyond wheel detection, by means of serial interfaces of evaluation boards to higher-level applications, opens up a wide range of functional possibilities not yet used today, especially in highly integrated complex electronic interlocking systems.

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■ ZUSAMMENFASSUNG

Die Herausforderung an Raddetektion und Achszählung in der Zukunft

Achszählsysteme mit induktiven Radsensoren haben sich bereits bei vielen Bahnen weltweit als zuverlässige und wirtschaftliche Gleisfreimeldesysteme etabliert. Das Fortschreiten des Standes der Technik in den Wirkprinzipien, den Herstellungsverfahren und Werkstoffen sowie die mittlerweile jahrzehntelangen Einsatzerfahrungen bildet die Grundlage für immer mehr Anwendungen und Lösungen. Die Entwicklung auf dem Fahrzeugsektor hinsichtlich Typenvielfalt, elektromagnetische Emissionen und Geschwindigkeiten stellt weiterhin höchste Herausforderungen an die Radsensoren, um eine sichere und zuverlässige Raddetektion zu gewährleisten.