Broken Rail Detection Systems

State of the art analysis
Report

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1 SUMMARY

Brocken rail is one of the challenges that railway companies are facing. Rail breakage still occurs frequently on railway networks all over the world. The most contributing factors to rail break are deteriorating rail conditions, loads from annual gross tonnage, degrees of curvatures as well as temperature among others. Statistics show that in the European Union broken rails are the main precursor of accidents. Broken rails are identified to be the most important contributors to derailments. Hence, infrastructure managers are forced to find a solution for continuous monitoring of rail condition, so that safety, punctuality and lower maintenance costs are guaranteed. The detection of broken rails itself is not a new topic. The most common method today for BRD is track-circuit. Now a days, the rail networks are being equipped with axle counters or block manuals, ETCS Level 2 and in the future ECTS Level 3 that make the use of track circuits redundant. Those advanced systems use smart training positioning or satellite localizations. Furthermore new track technologies in infrastructure (slab track, concrete sleeper...) and new rolling stock technologies (permanent slippage, high acceleration...) can lead to new type of rail defects. Therefore compatible technologies for a reliable and cost efficient detection of broken rails have to be considered. In this context, UIC started a project to define and demonstrate a new concept for a permanent broken rail detection. As one of the work packages of this project: state of the art of broken rail detection technologies were assessed. The assessment result shows that many efforts are being done to improve the reliability and efficiency of broken rail detection in many countries. However, most of the developments are still at the research level. This report classifies the systems into track mounted and vehicle mounted BRD systems as well as reactive systems that identify a broken rail after it has occurred and pro-active systems that find rail defects that can become broken rail in the future. Advantages and disadvantages of each system are described. Technologies that are currently being used in other branches and can potentially be employed to detect rail breaks are provided. Furthermore, the report presents the evaluation results of a survey conducted through questionnaires sent to stakeholders. As the result of the evaluation 87% of participants of the survey responded that the issue of broken rail is very important to extremely important to their company. 66% of them responded that accidents caused by broken rail are rare however up to 25% of the consequences are sever. It can be inferred that although the probability of occurrences are low they cause potential high risk train accidents. The most important limitations to use BRD systems as mentioned by stakeholders are speed limits; the systems are applicable only to secondary lines. 75% percent of the respondents know BRD systems other that track circuits. They mentioned systems such as fiber optic, ultrasonic, rail sonic, eddy current. The limitations of those systems are reported to be shorter detection range, detections are not effective and to be detected the rail muss have already been completely broken.

2 Background

Within a competitive environment one of the most important factors that a railway system should ensure is an operational safety. For ensuring railway track safety, different techniques are being applied to detect rail track failures. On top of that, the growing demand for interoperability across European countries incited the European Commission to analyze and remove the technical barriers against interoperability regarding the train control command system for cross boarder operations. As a result the European Train Control system (ETCS) that offers a uniform signaling system for cross boarder operations was developed. ETCS is evolving. On the ETCS side, the vision is based on the exchange of information between the on-board and the trackside equipment through an IP network. The performance of ECTS Level 2 and Level 3 relies (in addition to parallel evolutions in ETCS) on transmission speed and quality. For the future of (mainline) signaling systems based on ERTMS Level 3, an accurate, continuous and safe position data will need to be supplied to the control center directly by the train, rather than by track-based detection equipment. As the train continuously monitors its own position, there will be no need for 'fixed blocks'; rather the train itself will be considered as a 'moving block'. No more track circuits or axle counters will be necessary for the detection of the trains. In fact, those developments will increase capacity on the railway lines but they also entail some problems related to broken rail detection.

Track circuit based signaling broken rail detection systems, besides the fact that they are not installed in all the lines, they have many limitations [1]. When more trains that are running on the track the detection performance of the system decreases. The system furthermore, cannot detect all types of rail breaks. Other actions such as earthing and bonding may provide an alternative path for the track circuit current, bypassing the rail breaks. The Author above also mentioned that if the track circuit voltage is adjusted too high, a break may be bridged by voltage traveling through contaminated ballast.

2.1 Frequency of rail failures _ broken rail

To verify safety risks on the railway sector in the European Union, the European Railway Agency (ERA) has established a Safety Management System (SMS). In this SMS, all railway companies from the member states are encouraged to report irregularities and accidents. This facilitated statistical evaluation safety critical areas in the railway system. Important elements of the SMS are the precursors of accidents that are incidents where no damages have occurred, but under certain circumstances an accident could happen. Figure (1) shows the event chain of an accident occurrence and possibility of prevention by identifying the crucial point. In this chain the crucial point are the precursors. A precursor is any incident or group of incidents that mostly lead to an accident. When this incident (precursor) is detected, it is possible to avoid an accident by corrective action. If the precursor is not detected or ignored, there may be an accident.

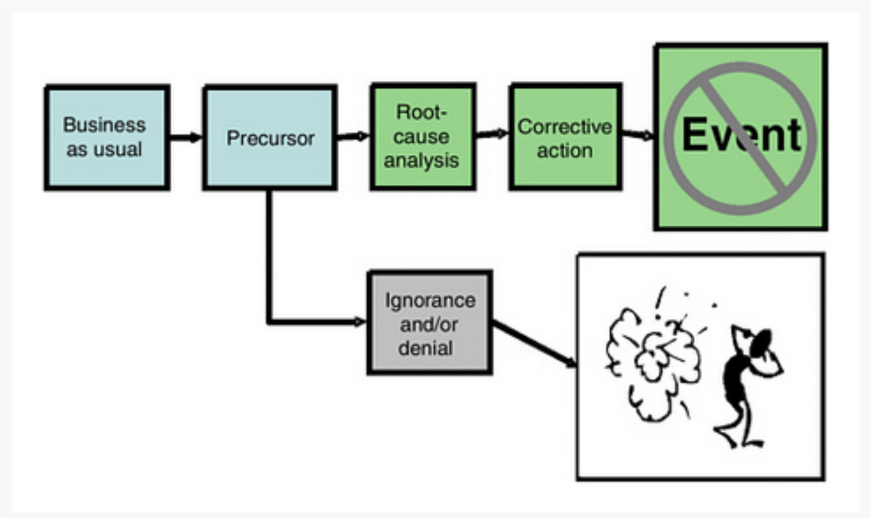


Figure 1: The arise of an accident and opportunities to avoid them [2]

The evaluation of the total precursors of accidents in the European railway track systems from 2010 to 2012 showed that by far the greatest rate of the incidents were caused by rail breaks followed by track buckles and wrong side – signaling failures (Figure 2).

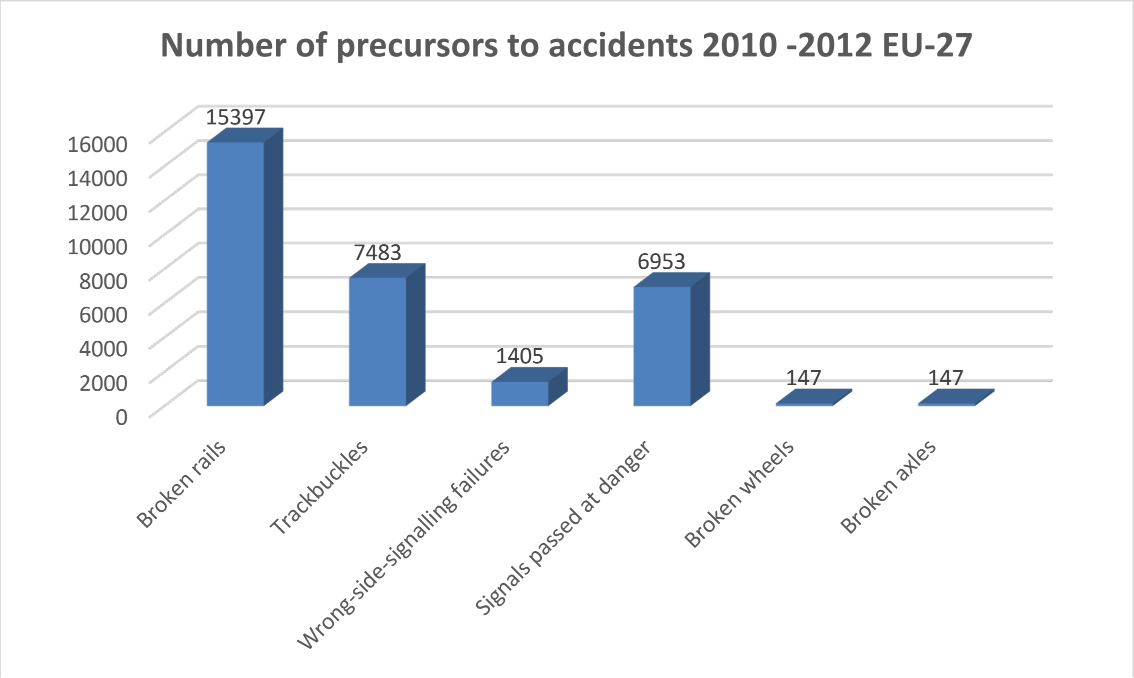


Figure 2: Precursors of accidents in the railway tracks systems of EU

Vehicle-based inspections are currently being used to figure out faulty rails. However, such measurements can only take place periodically, mostly few times a year. Based on those measurements, the condition of the track is analyzed and rails will be replaced in case of damage or excessive wear. However, the causes of broken rail that may happen between the times of the periodic surveillances will not be detected. This has the consequence that trains could derail when they pass a broken rail. Hence, detection of rail breakage during the time between periodic inspections using permanent monitoring system on the railway track could minimize potential risks in the railway service. An additional value of such a broken rail detection system would then simultaneous collection and record of data on further track quality parameters. One of those parameters is for example track buckling that is second major precursor of accidents in the EU (Figure 2).

3 Broken rail detection systems

Now a days advanced non-destructive test (NDT) techniques are being implemented for periodical track inspection. Track inspection systems utilize different techniques to capture rail defects and precisely locate rail defects along the track. Rail defects mainly include problems related to weld, internal defects, worn out rails, head checks, squats, spalling and shelling, surface cracks that are originated from rolling contact fatigue (RCF). Railway infrastructure owners endeavor to prevent these defects in order to reduce the probability of the occurrence of rail breaks and related accidents.

Periodic inspections are carried out by multi-functional track measuring trains that can take various measurements simultaneously. The geographical position of the track defects are also precisely located by GPS that is mounted on the inspection car. The frequency of those measurements in a given period of time depends on line categories (track load). Despite those regular inspections there is usually a potential risk of rail breaks that may cause very serious train accidents. In order to capture those faults continuous systems are demanded.

Currently, there are a large number of broken rail detection systems that are either mounted on rail vehicles or on the track itself. In addition, there are manual systems of measurements to find out local faults. The following section will provide a brief overview of the measurement techniques for broken rail detection.

- Electrical circuits

- Optical
- Video
- Laser scan
- Fibreglass sensor

- Ultrasonic
- Pulse-echo mode
- Through-transmission mode

- Elastic wave analyses method

- Magnetic flux leakage (induction)

- Eddy-current
- Electro-Magnetic Acoustic Transducer (EMAT)
- Strain gauges
- Galvanic (track circuits)
- Accelerometer

For material testing in a laboratory environment, there are many more measurement techniques, but those are not treated here.

In the following sub-sections, brief descriptions of the detection systems based on their character: (i) track mounted vs vehicle mounted as well as (ii) reactive systems that find a broken rail after it has occurred and pro-active systems that find rail defects that can become broken rail in the future.

3.1 Track mounted systems

The measuring systems are permanently mounted on the rail or on the track recording the rail condition in short period intervals. The interval length can be selected or adjusted individually based on the energy demand of the system and the availability of the power supply on site. Usually the measuring interval is no longer than then 15 minutes. Track mounted measuring systems vary in their way of capturing rail defects and their performance. Some systems can only detect a rail break that has already been occurred. On the other hand, systems such as fiber glass sensors for instance detect a large number of irregularities on the rail proactively.

Technologies that are used for the track mounted broken rail detection are described shortly as follows:

- Fibre glass sensors
  Depending on the technology, either only a rail break is detected, or further important parameters e.g. track buckling
- Strain gauges
  Measures the change in stress. The temperature and stress are measured and analyzed, the combinations of stress and temperature indicate a rail break.
- Ultrasonic, through transmission mode
  Ultrasonic waves passing through the rail will be analyzed. In case of a rail break, these waves are interrupted and the break is detected.
- Elastic wave analyses method
  As a result of the mechanical effect of a train on the rail, it is possible to infer the rail condition in its surrounding
- Electrical circuits
  A source of electric current is applied between two stations (insulated joints) so that electric currents flow in both rails. The voltage difference between the two sections indicate the rail break.

3.2 Rail vehicle mounted systems

In the case of vehicle-based measuring systems, the sensor system is usually mounted just above the top of the rail. The possible speed where measurements could take place varies strongly depending on the sensor system (for example, ultrasonic <100 km/h, video ≤ 250 km/h). This results in different occupation times of the railway lines for measurements that in turn have negative impact on the track capacity. The measurements are carried out repeatedly depending on the load and importance level of the track. Since the measurements are periodical, it is important to plan future measurements precisely, so that unacceptable track defects can be captured before they pose risks to the train traffic until the next measurement takes place. Inspection using multi – function track recording cars have favorable impact on the cost efficiency, because of the possibility of recording various parameters at the same time as well as precise identification of the location of the defects [3]. The following techniques are used to monitor the rail condition:

- Video recordings
  High-resolution cameras are directed at various angles on the rail, which can be used to identify damages on the track (e.g., loose parts)
- Ultrasonic, pulse echo mode:
  An ultrasonic signal passes through the rail vertically and is reflected back due the bottom of the rail. Faults can be detected by the recovered signals.
- Magnetic flux leakage:
  A high current is introduced into the rail under the measuring vehicle, resulting in a homogeneous magnetic field. If the rail has surface defects, the magnetic field is disturbed and the fault could be detected.
- Eddy-current:
  An oscillating magnetic field is introduced from the vehicle into the rail, due to the behaviour of the magnetic field in the rail, near surface defects could be determined.
- Electro-Magnetic Acoustic Transducer (EMAT)
  Functions similar to ultrasound, but electromagnetic waves are used to induce the sound waves into the rail

Due to the large number of vehicle-based measuring methods, all relevant track parameters can be measured as well as broken rails can be detected. Since these measured values are generated under the load on the track, they are also realistic, and the track behaves as like under normal load in train traffic.

3.3 Reactive vs. proactive detection Systems

Broken rail detection methods can be distinguished in reactive and proactive systems. Reactive systems identify a broken rail after it has occurred and pro-active systems find rail defects that can become broken rail in the future. In case of the reactive systems no information on the condition of the rail will be available ahead so that it is assumed that the rail is in a safe condition until the break happens. This means in case a slight break of rail has already occurred, no warning signals will be available for the next train that passes over the damaged rail which lead the rail to be completely broken. In case of proactive systems, the rail condition is periodically monitored. As a result, changes in the track are already detected. Emanating from these changes it is possible to infer the further development of the track.

In general, it can be said that vehicle-based measurement methods have a proactive character (ultrasound, induction, etc.). In the past, track-based measurement methods, e.g. track circuits are usually reactive systems. However, the evolutionary progress of the track-bound measurement methods is leading to the proactive character of those systems. For instance, it is currently possible to detect the tensions in the rail by means of glass fiber sensors that are attached to anticipate the probable breakage of the rail. As a further example, a track-bonded ultrasound method could be mentioned, because such systems could nowadays also detect large cracks in the rail.

The following section describes different technologies implemented in the track mounted detection systems.

4 Description of track mounted BRD systems

4.1 Fibre optics

Fibre optics transmit information over a large distance through light waveguides. They can also be used as sensors. The basic idea for this sensor system is the fact that mechanical influences change the light signal in the fibre optic. Those deviations can be measured and enable to make statements about the mechanical influences in the glass fibre.

The simplest application of a fibre optic sensor for broken rail detection is to install them on the rail web. The glass fibre is flooded by light pulses that are generated by a laser, the wavelength of the pulses is commonly 1550nm. At the other end of the fibre optic cable, a receiver is installed to evaluate those signals. If the rail breaks, the monitored section is interrupted and the receiver cannot detect any light pulses. When this happens, an alert message will be generated and the trains could be warned that a rail break has occurred. In the case of a slightly broken rail, where the fibre optic is not completely broken the receiver could also detect the rail break, by the drop of the signal strength[4]. If the transmitter is equipped with an optical time domain reflectometry (OTDR), it is also possible to localise the geographical position of the breakage.

A feasibility study conducted by the Transportation Technology Center, Colorado [5] on the detection of broken rail using fiber optics showed the advantage of the system in detecting weld cracks before a full breakage occurs, as well as rail buckling. The authors mentioned that the system is more advantageous in the sections where insulated joints are rare. The disadvantage of those systems are reported to be their demand for clean surfaces where the epoxy should effectively adhere to the rail and fragility and demand of extreme care during installation and repair. The authors furthermore mentioned that the application distance is limited to 900m.

In recent years the fibre sensor technology has developed strongly and currently it is possible to detect further parameters. However, some of these new technologies are still at development stage and have not yet been tested in the field. The most important and also promising technologies are briefly listed below.

4.1.1 Fiber Bragg Grating (FBG)

A fibre Bragg grating is a microstructure that is incorporated in a single mode fibre. This fibre Bragg grating reflects a narrow band of the light spectrum introduced by the laser, back to the transmitting unit. This unit is also equipped with a detector that can analyse the reflected light.

The spectrum of the reflected light depends mainly on the microstructure and the refraction index of the core fibre. With no external influences on the fibre optic, the reflected frequency spectrum remains constant.

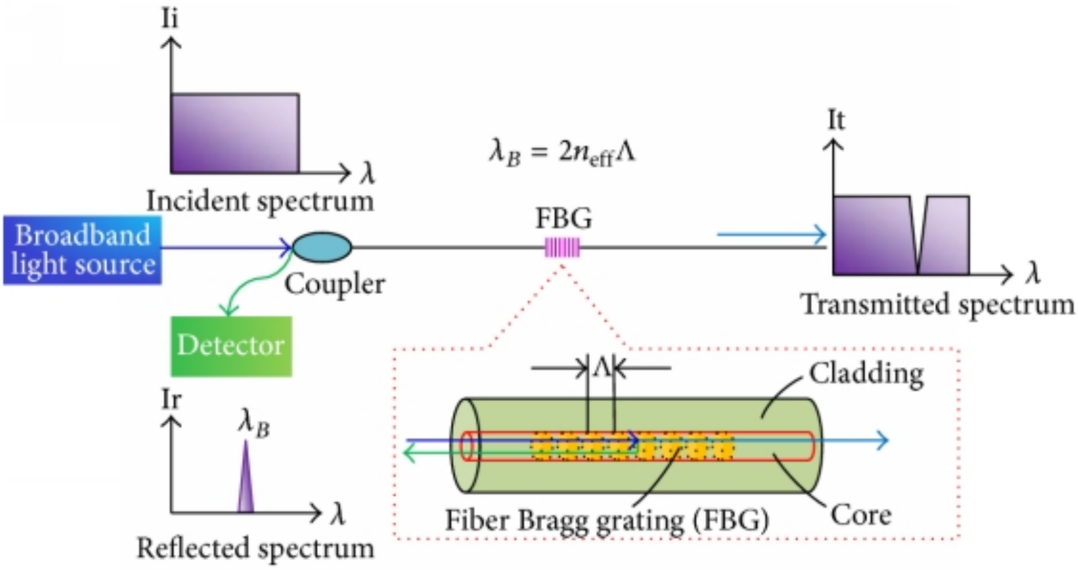


Figure 2: Measurement principal of FBG sensors [6]

If the periodic variation in or the refractive index of the fibre changes, the reflected light spectrum shifts (e.g. the grating period can be varied by stress and the refractive index be changed by temperature). Deviations in response to variations in temperature and/or strain can be measured and conclusions can be made about the current state of the glass fibre on the track. Due to the multiplexing capability of this technology, it is possible to accommodate a large number of sensors in one fibre optic cable. The advantage of the FBG-technology is, that it cannot only detect rail breakages, but also track geometry, the position of the train as well as speed, axle loads and flat wheels [7]. This system has already been tested in a field study on the Madrid-Barcelona high-speed line [8].

4.1.2 Brillouin Optical Time Domain Reflectometer (BOTDR) and Brillouin Optical Domain Analyzer (BOTDA)

In the BOTDR/BOTDA method, the theory of stimulated Brillouin scattering (SBS) is applied. By laser action in the optical fibre, its lattice structure begins to oscillate. On this lattice structure the laser light is also partially reflected. Depending on the oscillation of the material, the reflected light undergoes a frequency shift. This spectral shift can be measured as well as analysed and the position of the measurement in the optical fibre can be determined based on the transit times of the reflected light [9]. Due to its strong dependence of the crystal oscillations of the glass fibre on environmental variables, such as temperature and strain, it is also possible to measure those parameters. Figure (3) shows a schematic BOTDR measurement, in the area where a pressure applied to the fibre optic and a frequency shift eventuates on the backscattering signal.

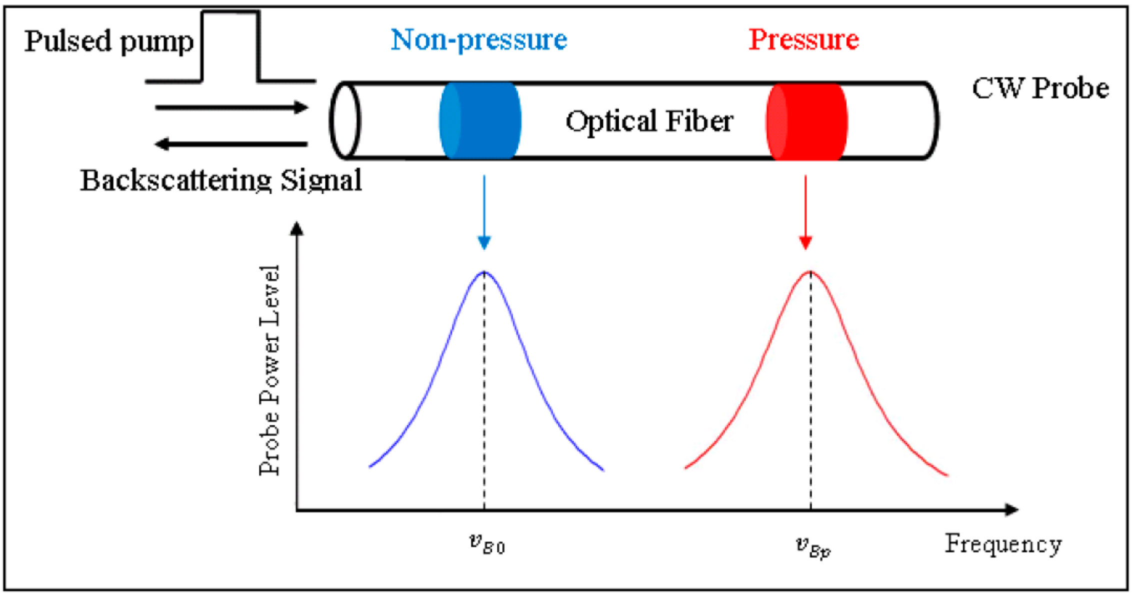


Figure 3: Schematic BOTDR measurement [10]

With the SBS technology it is possible to achieve measuring distances of up to 100km. The expansion resolution is in the best case $2*10^{-6}$, the temperature resolution is 0.1 degree. However, because of their mutual influence, it is impossible to measure both parameters in their highest resolution at the same time. Such sensors are currently being used in monitoring bridges, pipelines, high-voltage lines and fire detection in buildings [11, p. 392].

4.1.3 Distributed Acoustic Sensing (DAS)/Distributed Vibration Sensing (DVS)

A DAS sometimes referred as DVS measurement system is based on the fact that materials get minimal changes in their dimensions under influence of sound waves, temperature or mechanical vibrations. In case of glass fibre, the glass molecules are stimulated to oscillate during the length variation, triggered by mechanical waves. When a laser pulse passes through the glass fibre, it will be partially reflected by the oscillating molecules. Depending on the oscillation intensity of the glass molecules, the reflected laser pulse gets a spectrum shift. This spectral shift can be detected (Rayleigh scattering) and the position of the reflection in the optical fibre can be detected by the signal running time (Figure 4) [12].

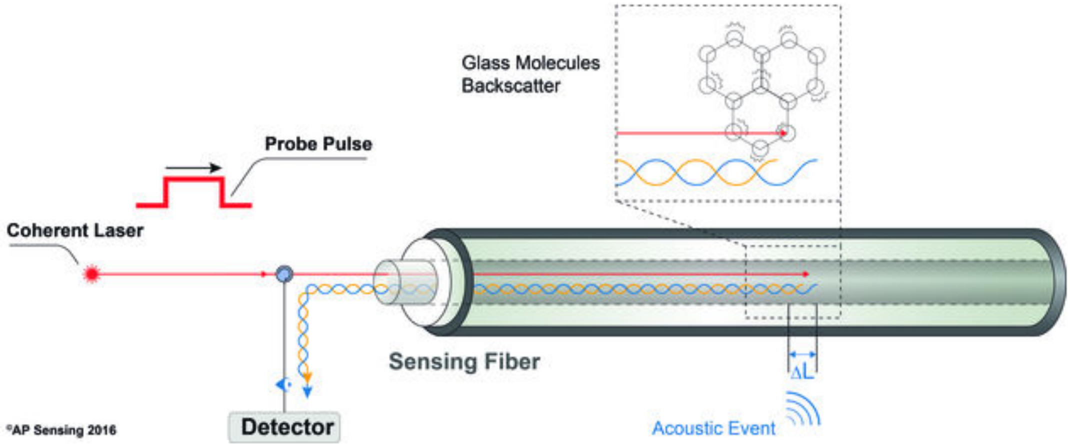


Figure 4: Schematic illustration of a DAS sensor [13]

This technology allows measurement distance up to 40km with a virtual sensor interval of 1 meter. Measureable sizes for this system are mechanical waves and temperature, consequently a change in the rail oscillation may indicate a rail break. This System is mainly used in geophysics to detect seismic activities [14]. Furthermore, DAS systems are used in real-time monitoring on oil and gas pipelines [15]. Such system may be interesting for track monitoring, because the fibre optic does not need to be located directly on the rail and would be better protected during track maintenance works.

Currently, two companies tried to develop a DAS System for the railway superstructure. One of them is Next Generation Rail Technologies S.L., Spain (https://www.ngrt.org/) and the other is Frauscher Sensortechnik GmbH, Austria (http://www.frauscher.com/en/tracking/). However, it is not known how far those development of the systems by those companies being advanced.

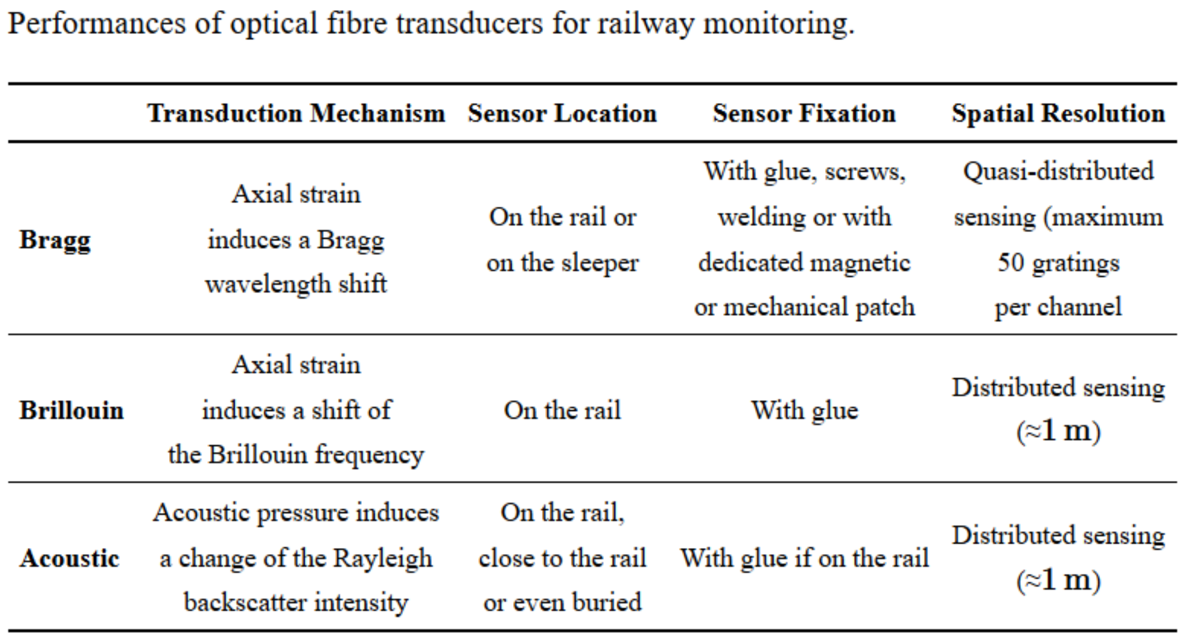
4.1.4 Summary of fibre optic system

Optical sensor system can detect different parameters. If the system simply consists of an OTDR unit, only the break with respect to the damage and geographical location of the damaged fibre optic can be detected. Identification of the damaged optic cable will support to infer the state of the rail pinpoint the broken rail.

The further developments of the fibre optic measurement technologies (FBG, BOTDR, BOTDA, DAS, DVS), enable the quantification of additional relevant parameters in the inspection of rail infrastructure. Those technologies measure strain and temperature allowing to infer rail break, track buckling, axle loads, train detection, train speeds, rockslides, etc. Thus, facilitate real-time statements about the infrastructure. However, such optical fibre sensor systems are currently being used only in monitoring pipelines. Their application in the railway infrastructures are very infant and are still at the stage of research.

Table (1) shows a short comparison of those three fibre optic technologies.

Table 1: Optical fibre transducers for railway monitoring [7]



Performances of optical fibre transducers for railway monitoring.

	Transduction Mechanism	Sensor Location	Sensor Fixation	Spatial Resolution
Bragg	Axial strain induces a Bragg wavelength shift	On the rail or on the sleeper	With glue, screws, welding or with dedicated magnetic or mechanical patch	Quasi-distributed sensing (maximum 50 gratings per channel
Brillouin	Axial strain induces a shift of the Brillouin frequency	On the rail	With glue	Distributed sensing (≈1 m)
Acoustic	Acoustic pressure induces a change of the Rayleigh backscatter intensity	On the rail, close to the rail or even buried	With glue if on the rail	Distributed sensing (≈1 m)

Advantages of fibre optics

- Track monitoring in real-time
- Insensitive to electromagnetic and radio frequency influences
- Depending from the sensor-technology, not only rail break could be detected, but also a variety of other abnormalities in the track (cracks, strain, geometry, etc.) up to rail vehicle specific parameters
- Promising over very short distances that are difficult to insulate and
- For each rail only one fiber optic, no other equipment on the railway line is required.

Disadvantages of fibre optics

- Demand of clean surfaces so that the epoxy effectively adheres to the rail
- High requirements on the glue, which fixes the glass fiber to the rail (durability)
- Easily damaged during ballast damping or other track works
- In case of a break, a fibre optic is complex to repair

4.2 Strain gauges

Strain gauge - strip of conductive metal measures material tension; where the change in electrical resistance of the strain gauge are caused by a stretching or compressive force. Strain gauges measuring the effective tension of the full-length of a rail demand that the measuring units not be further apart than 60m. Commonly, the interval for strain gauges are 30-60m, on both rails. Figure (4) shows a strain gauge unit which is mounted on the rail web. The rail tension can be used to deduce the state of the rail, this means, if the rail tension drops significantly, the probability of a potential rail break is quite high. In addition, it is possible to detect deformations in the track geometry. In order to assure durable connection between the strain gauge and the rail web, a micro weld seam is required. The sensors can be fixed on the rail, before the rail is mounted on the track, or afterwards. For calibrating the strain gauges, it is indispensable to cut the rail in several parts, to reset the rail into a zero tension condition. Subsequently, these sections are to be welded again.

The information transmission between the sensor and the receiving station can be carried out via cable, or even wireless. For a wireless design, the receiving station must not exceed the distance of 600 meters from the transmitting unit. This implies that a receiving station is demanded in every 1,2km on the straight line. The current wireless systems have a tracking rate of 10 minutes, this means that every 10 minutes the strain gauge unit transmits the current tension of the rail, hence a rail break can remain undetected for at least 10 minutes. At this tracking rate, the batteries of the measurement unit have a lifetime of 10 years. If the tracking rate is higher and shortens lifetime of the batteries lifetime, the measuring units can additionally be equipped with removable power packs [13].

Figure 5: Measuring unit based on strain gauges [17]

Strain gauge technology for broken rail detection, provided by Salient System, Inc., Dublin, Ohio, USA uses a number of strain gage sensors installed on the gage side of the rail at intervals of 30 to 60 m. Field test at the testing site of the Transportation Test Center in Pueblo, Colorado had been conducted to evaluate strain gauges that were applied to the rail at intervals of 60 m [18], [19].

The summary of the advantages and disadvantages of the technology are summarized as follows:

Advantages of strain gauges

- The strain gauge with transmission unit can be installed in less than half an hour by two persons
- Besides broken rail, the system also detects track buckling
- The detection system is ready for immediate use after a break is repaired

Disadvantages of strain gauges

- A purely reactive sensor
- The demand for shorter data collection intervals
- Not possible to have conventional bolted rail joints in the detection area that prevents installing rail plugs with bolted joints as a means to affect a quick repair to defects
- Lower sensitivity for rails that may break but not separate, that may happen when the rail is in compression
- To calibrate the system, a strainless rail is required. As a result, the mounted rail on the track have to cut in pieces. Subsequently, these pieces have to be welded again.

4.3 Acoustical method

The ultrasonic measurement method utilizes the effect that high-frequency sound waves are reflected at the transition zone from solid to gaseous substances. Those effect can be applied to detect rail breaks. For this application a high frequency sound wave is initiated into the rail. This happens mostly through the piezoelectric effect, where by a crystal is stimulated to oscillate triggered by external electric fields. At the other end of the measuring section is a detector that converts those vibrations into electrical signals. If the detector receives these waves, it can be assumed that the detected path is intact and there is no rail break. On the other hand, if a rail break is present, no ultrasonic signal is received and an alert is initiated to warn trains in the damaged section. In order to receive a sufficiently intense signal at the detector, the measuring sections are limited to a maximum length of 1km. Hence, with 2 transmitter units and 1receiver unit it is possible to monitor a track length of 2km. The receiver unit is linked with a transmitter station to convey the information about the track state [20] (Theoretically, information transmission by means of sound waves in the rail itself would also be possible, but with a very low bit rate and various disturbing influences [21]). Figure (6) shows the schematic setup from an ultrasonic-monitoring system to detect rail breaks. This facility is located in South Africa which is installed on 840km of a heavy duty rail line. Due to the favorable solar radiation in South Africa, the energy supply of the system components can be covered by solar panels, so no connection to a power grid is necessary. The tracking rate from the system is 15 minutes, so a broken rail can detect at least after 15 minutes. The facility can currently detect rail breaks and in the future this system also should monitoring partially fractured rails. However, the ultrasonic measurement is only possible by continuously welded tracks. Weather conditions such as rain or snow may also distort the measurement results.

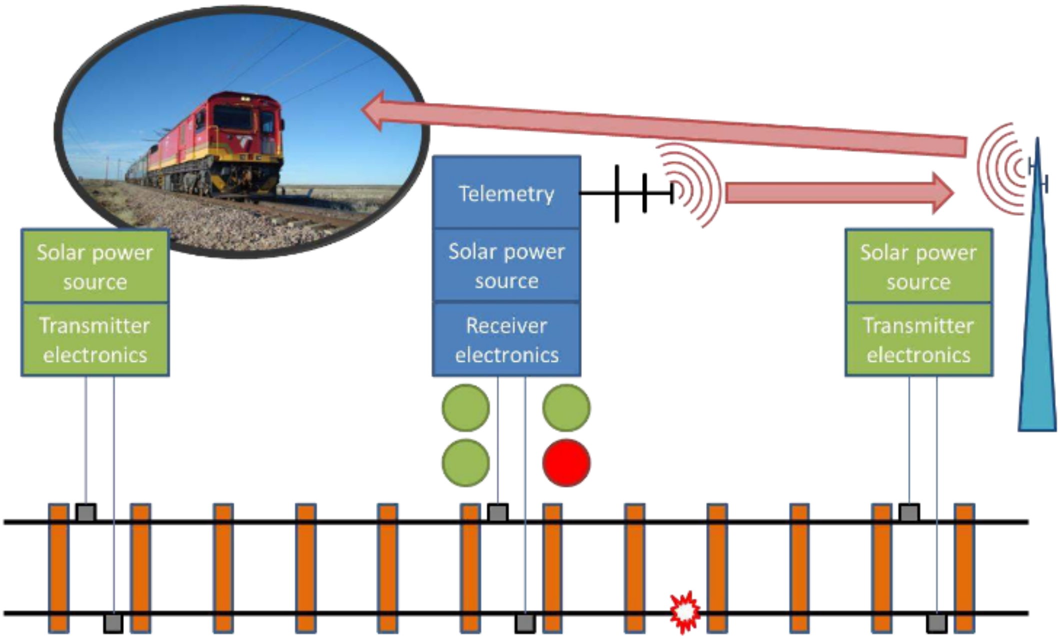


Figure 6: Ultrasonic broken rail detection facility (South Africa) [20]

Based on the findings of the authors mentioned above and the research report of [22], the advantages and disadvantages of the acoustical method in broken rail detection are summarized as follows:

Advantages

- This System can detect rail breaks and also 80% cracked rails
- The system would use acoustic propagation in the rail as a digital communication network.
- This allows the system to provide broken rail protection without the installation of an additional wayside communication system
- Hence no additional cables for communication are required

Disadvantages

- Significant problems with mechanical joints (particularly, temporary joints used to patch rail defects) were encountered
- The range is limited to short distances (ca 1 km)
- Environmental studies indicate that the optimal frequencies change 100 to 200 Hertz over the day-night cycle, and rain strongly attenuates the signal

4.4 Elastic wave analysis method

When a rail vehicle moves over the tracks, sound and ultrasonic waves will be generated in the rail as a result of the rolling contact. These waves spread out along the rail, in different manner depending on the condition of the track superstructure. In the most unfavorable case they spread in more than 1km distance. These vibrations can be detected by sensors that are mounted on the rail. If the rail between two sensors is interrupted (such as rail breakage), the amplitude decreases significantly at the sensor which is located after the break. By comparison of at least two received signals, a rail break can be detected (Figure 7). Through the reflection of the waves from the broken back to senor 1, it is also possible to localize the position of the broken rail [23].

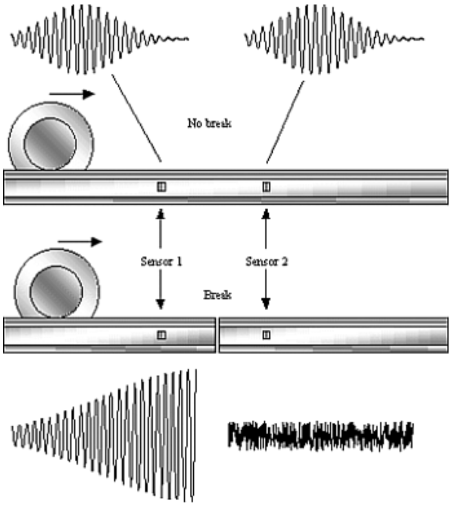


Figure 7: Elastic wave analysis of an rail [23]

Advantages

- No transmitter required, because the train generates the measuring signal

Disadvantages

- Eventual problems related to different superstructures in regard to the attenuation of the signal
- A variety of rail vehicles produce different acoustic signals in the rail in relation to distinct axle distances, suspension, etc.; hence, a precise evaluation and interpretation of the induced sound waves would be difficult.

4.5 Electrical circuits

Broken rail detection by electrical circuits is installed and tested by SNCF-Reseau in a distance of 3 x 10km with 1m gauge track section in the Eastern Pyrenees between the stations of Latour-de-Carol-Enveitg, Font-Romeu-Odeillo-Via, and Villefranche - Vernet-les-Bains [1], in an electrified line with third rail at 850 V DC.

The track is totally laid out on wooden sleepers with a 46 Kg/m rail profile in jointed track.

The detection zone are defined by two stations where an electric current is applied between the two stations, where an electric current is applied by means of two tuning units, each one connected to each rail of the track, transmitting current at a voltage of 220V and frequency of 50Hz. The detection zones are defined between two different stations. Earthings are connected within the track axis and the sidings of the track.

Unequal voltage difference between the sections of the track reveals the rail, breakage forcing the opening of the output relay, in case of happening

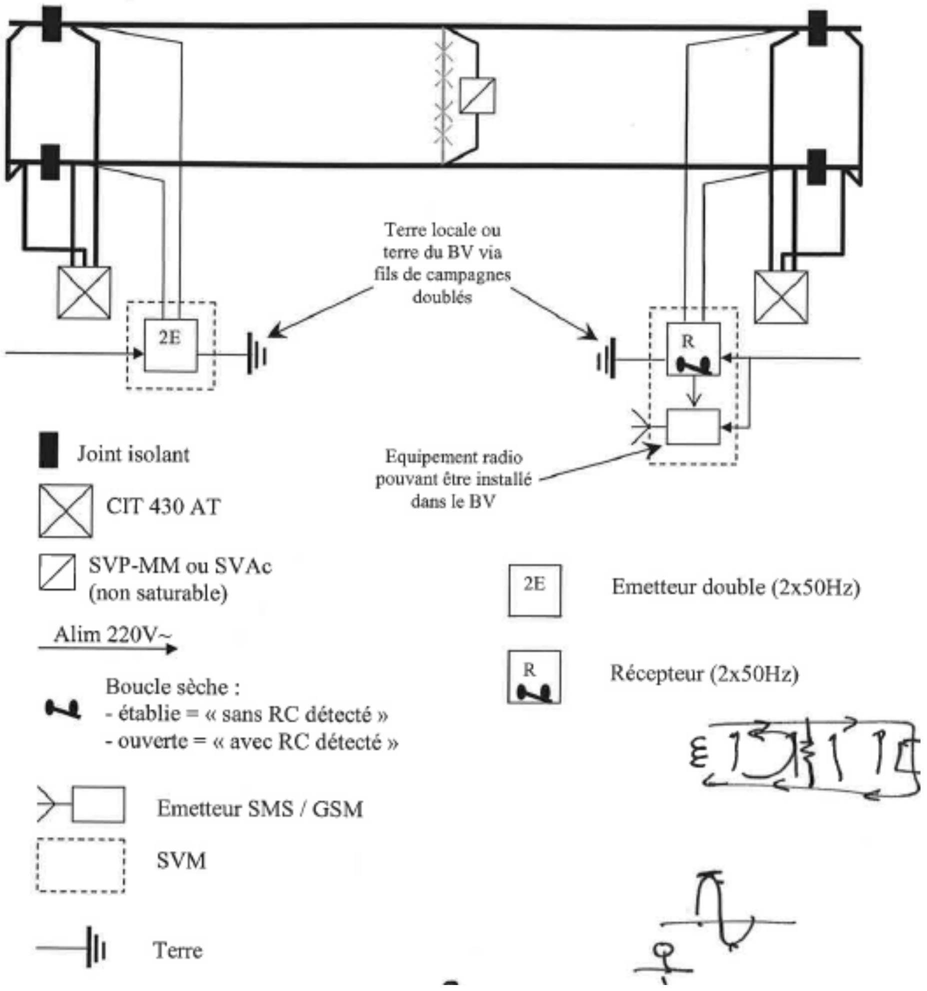


Figure 8: Electrical circuit for BRD [1]

The detection is not precise in terms of location distance from both ends, but is able to offer a general idea of the section in which the breakage is placed, and is exact to which of both rails is affected by the breakage.

The relay was connected to a transmitter of SMS based in GSM network connection. In which complex information can be transmitted (breakage (yes/no), left/right rail, difference of voltage, section). New IoT technologies could currently analyze and benefit of that information at a low cost.

The idea can be applied to switches and crossings, independent of their total length, installing inductive loops in between isolated joints (much more needed when S&Cs are longer), connecting the switch rail and counter rail of each side in the switch area, external and internal rails in the crossing area, and after the crossing, up until its end, the external rail in direct and diverted track, and also the internal rail of both tracks. Earthings must be done per track in this final section.

Advantages

- Detection with/without train presence
- Able to monitor up to 15km, for direct current (DC) and 30km for alternative current.
- Valid for CWR-continuously welded rails or jointed track (isolating joints are necessary)
- Could be used with supply even different voltage currents by means of use of a power transformer and also with lower frequencies (16 or 25 Hz)
- In switches and crossings, also the variation of direction of current intensity could be measured, in order to locate precisely in which section, the breakage has happened
- The system may be certified Safety Integrity Level (SIL) 2

5 Description of vehicle mounted BRD systems

5.1 Wavelets from accelerometer

This detection system is based on acceleration sensors that are mounted on the axle bearings or bogies of rail vehicles. The basic consideration in this system is that various rail errors have different effects on the accelerations of the vehicle mass. The challenge however is, that even the occurrence of a minor faults should be detected. Because such minor faults could rapidly grow within few train overruns. If a rail fault gets large, it can lead to derailments. In order to capture those small faults, an algorithm that makes these irregularities visible has been developed. The algorithm is based on the Fourier transformation and Wavelet transformation. For classification of the faults, the wavelet-processed data is fed into an artificial neural network. A combination of signal processing wavelets and a self-learning neural network enable to classify defects between full breaks and rail head cracks that will likely develop into full breaks [24].

This system was tested in the Facility for Accelerated Service Testing (FAST) in Pueblo, Colorado [25] at metro car (Metro Nuremberg) Germany [26].

Advantages

- The system is able to classify defects between full breaks and rail head cracks that will likely develop into full breaks.
- Nevertheless, this technology illustrating the advanced state of signal processing available for reactive sensors

Disadvantages

- It is unlikely that this technology will detect defects outside the running surface
- The algorithm was unable to successfully identify a high percentage of true rail breaks while maintaining a low overall false positive rate

5.2 Time domain Reflectometry (TDR)

With a TDR, it is possible to locate fractures in electrical conductors. This technique is mainly applied in network technology, but it is also possible use it for rail track monitoring. In the case of broken rail detection, the TDR is mounted on the leading traction vehicle. The TDR sends radio waves (RF) into the rail, these waves propagate longitudinally in the rails ahead of the train depending on their frequency and pulse strength. When there are irregularities in the rail (e.g. rail break) the impedance changes, this can be detected. Furthermore, the RF signal is reflected at a potential fracture site and the distance of the rail fracture can be deduced by the travel time of the reflected waves (pulse/echo). This enables warning of the engine driver to stop the train before the rail is broken. This system also stores a back to the train protection system, since an occupied track by another rail vehicle will also be detected [27].

Depending on the characteristic of the track structure, the RF signal is attenuated differently that greatly reduces the range for broken rail detection. Furthermore, switches and insulated joints also have an unfavorable effect on the signal strength. In table (2), the different ranges of the RF signal are shown in terms of their strength and the track layout.

Table 2: Maximum range for broken rail detection verses transmit pulse power[27]

Track Conditions		**Range (Miles) Verses Transmit Power**					
Ballast	**Tie Type**	**100 mW**	**1 W**	**10 W**	**100 W**	**1,000 W**	**10,000 W**
Wet	Wood	0.74	0.79	0.84	0.90	0.95	1.00
Wet	Concrete	0.82	0.87	0.93	0.99	1.05	1.10
Dry	Wood	1.48	1.58	1.68	1.78	1.88	1.99
Dry	Concrete	2.98	3.19	3.40	3.60	3.80	4.00

Challenges in the application of this system could arise from the fact that in Europe many different train protection systems or track circuits operate with different frequencies, which could be disturbed by this RF for broken rail detection. As an example, detection frequencies for broken rails are between 50 - 500 kHz, the ASFA (Renfe) train protection system uses frequencies of 55 - 115 kHz [28].

Advantages
- Backup to train protection system. Also detects unusual track occupations such as detached or runaway freight cars.
- Not affected by welds, rail repairs, bolted joints (with usual bond wires), bolt holes, etc.

Disadvantages
- The range in front of the train is limited
- The used frequency may disturb train protection systems/track circuits
- Well short of the required safe braking distance required by normal freight train operation
- Conventional bolted rail joints lower the sensors ability to perform as intended
- As a reactive sensor, it also suffers from the fact that the rail break has already occurred for the detection to take place
- Partial breaks, breaks on tie plates, and breaks under compression might not be detected because a significant loss of electrical continuity is required

5.3 Vehicle based ultrasonic systems

Rail vehicles for ultrasonic measurement mainly apply the pulse echo method. An ultrasonic signal is introduced into the rail, which is reflected back on the opposite side of the rail or by flaws. The evaluation of the echo signal can be used to infer the internal condition of the rail. With this method, small material defects will be visible and thus a potential rail breakage can be detected very early. Depending on the design of the measuring system, different areas of the rail can be monitored depending particularly on the angle of the ultrasonic sensors (Figure 8).

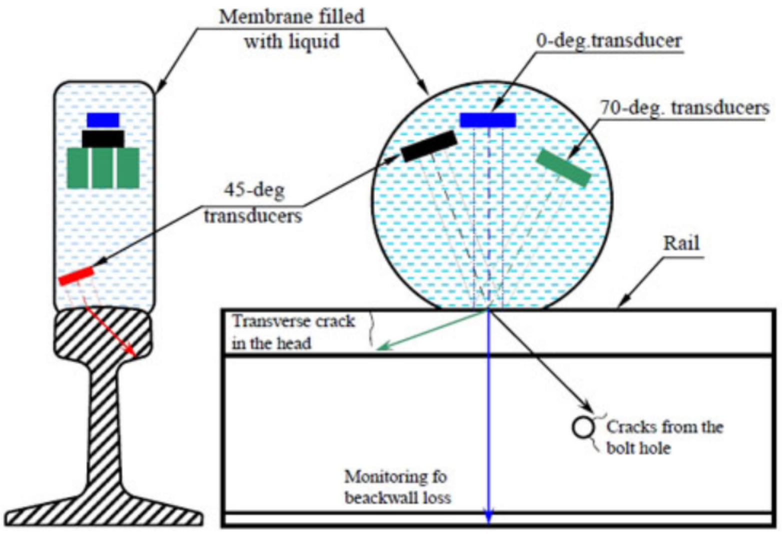


Figure 9: Ultrasonic probe arrangements from the company STARMANS, CZ

The ultrasonic sensors for rail inspection are often located in a wheel (Figure 8), because the sensors require contact with the object to be monitored. In order to improve the transmission of the ultrasonic waves into the rail, it is necessary to apply a coupling between the sensor wheel and the rail. An optimum ultrasonic based detection using a running vehicle is a given speed. As an example, the rail diagnostic train of MÁV Central Rail and Track Inspection Ltd. Is restricted to 50km/h during an ultrasound survey. [29]

In order to monitor shorter track sections by ultrasonic, there are compact ultrasound systems available that can be installed in an off-road - Road Rail Vehicle (RRV). This vehicle can be driven over the road to the inspection site. On the track the RRV – the ultrasonic detection takes place (Figure 9). After the measurement is completed, the RRV leaves the track and can take the road for transfer to the next site [30].

Figure 10: RRV with ultrasonic measuring equipment

Advantages

- A proactive system
- It is possible to detect faults and breaks in the whole rail (foot, web, head)
- Very common system

Disadvantages

- For detection of a broken rail, It should operates at speeds that are much lower than authorized train speeds
- Could force testing to be performed during off-peak times.
- In case of internal defects whose growth rate is faster than testing intervals, the defects may develop in to full break without prior to detection

5.4 Eddy current

By the eddy current test method, surface faults as well as faults near the surface of the rail can be detected. For this purpose, an alternate current is applied to a coil in the measuring unit near the rail surface. The alternating current in the primer coil results in an alternating magnetic field. If a conductive material (e.g. a rail steel) is in the vicinity of the influence of this magnetic field, eddy currents will be produced in this material. Since currents cause a magnetic field and also eddy currents. The magnetic field produced in the test material counteracts the magnetic field of the primer coil. If there is an error in the material to be tested, the magnetic flux of the eddy currents is changed, and also the magnetic field that counteract the primer coil. This results fluctuations in the magnetic field of the primer coil, which is noticeable in its current consumption. Hence, pinpointing the presence of material faults by means of deviations in the current absorption of the primer coil (Figure 10) will be possible. This example illustrates the simplest application of an eddy current measurement. In practical measurement setups more number of coils are used [31].

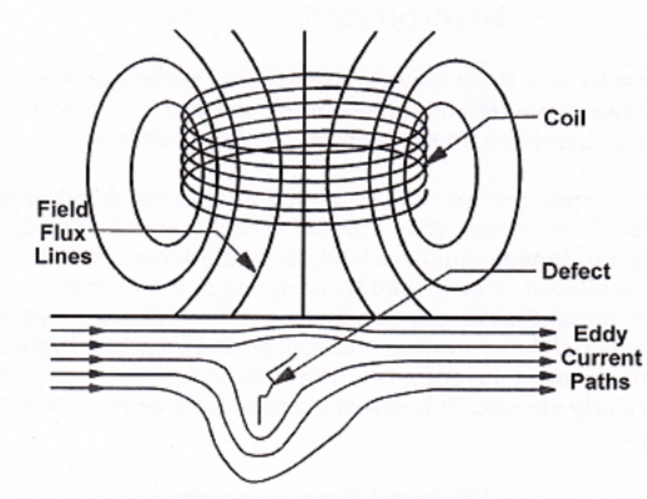


Figure 11: Eddy current example [32]

This system is used to detect rolling-contact fatigue (e.g. head checks). This type of rolling-contact fatigue is a very dangerous phenomenon of rail breakage, when the fine cracks have reached a certain depth, the entire rail can suddenly break.

Eddy current measurement and ultrasonic measurement are sometimes combined in order to obtain a better total resolution of the rail condition. For instance, the Deutsche Bahn (DB) rail test train (SPZ1) combines both systems. Eddy Current measurements are also used for local troubleshooting after rail maintenance work. For this purpose, the measuring device is mounted on a hand truck [33].

Advantages

- Detects roll-contact fatigue (Head Checks)
- This system is proactive, because it detects faults already in the initial phase
- Has higher resolution for surface defects than ultrasonic
- Inspection trains can be equipped with eddy current and ultrasound measurement technology, because these systems complement each other.

Disadvantages

- It has a small measuring range, only the surface and close sub-surface of the rail are examined.
- The speed during eddy current measurement in inspections trains is up to 80km/h

5.5 Magnetic flux leakage (MFL)

A magnetic flux is introduced into the material (rail) to be tested. The measuring instrument is attached to a rail vehicle. As the vehicle moves along the track, strong magnets are used to induce a magnetic flux into the rail. If no fault is detected in the rail, a homogeneous magnetic field will result. And a deviation in the magnetic fields indicate the presence of material fault in the rail. These differences in the magnetic field are detected by the hall sensor (Figure 10). However, by this detection method, faults that interfere with the magnetic flux can be identified. Cracks parallel to the magnetic flow cannot be detected [34]. MFL Systems are mainly used to monitor pipelines.

A similar monitoring method is used in the USA for rails. In contrast to the magnetic flux, electric current is conducted through the rail. Currents with up to 3600 amps are used depending on the cross section of the rail. That also results in a magnetic field produced around the rail that can in turn be detected [35].

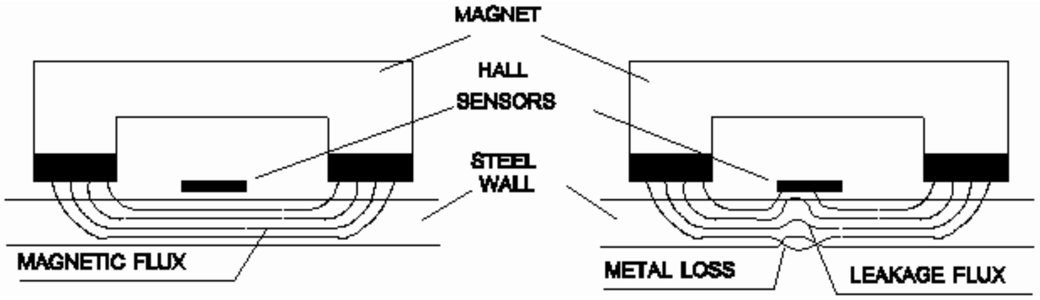


Figure 12: Principle of a magnetic flux leakage measurement [36]

Advantages:

- Detects mainly surface and near surface defects
- It is a proactive system

Disadvantages:

- Cannot detect cracks that run parallel to the magnetic flux
- Monitoring speed is relatively low, because with increasing speed the measurement quality deteriorates
- Insulated joints eventually interrupt the magnetic flux

5.6 Electro-Magnetic Acoustic Transducer (EMAT)

The EMAT test procedure is basically an ultrasound test. However, this method holds a great advantage over conventional ultrasonic measurement. The positive aspect is that the measuring unit does not need any direct contact with the object to be tested. Thus, the coupling problems of an ultrasonic measurement are bypassed.

The EMAT system is mounted near the rai surface on a rail vehicle which moves along the track. An electromagnetic wave is induced by EMAT in the metal object (e.g. rail) to be tested. This is achieved by the superposition of a static and an oscillating magnetic field in the transmitter unit. By the Lorenz force of these magnetic fields, a mechanical wave is transmitted into the rail, which is reflected on its underside. This reflection wave, in turn, has an effect on the induced magnetic field, which makes it possible to measure this reflection. If cracks are present in the rail, these can be detected by different wave travel times as in the case of an ultrasonic measurement. Figure (12) shows the schematic structure of an EMAT transmitter and receiver unit, which is used to monitoring pipelines.[37]

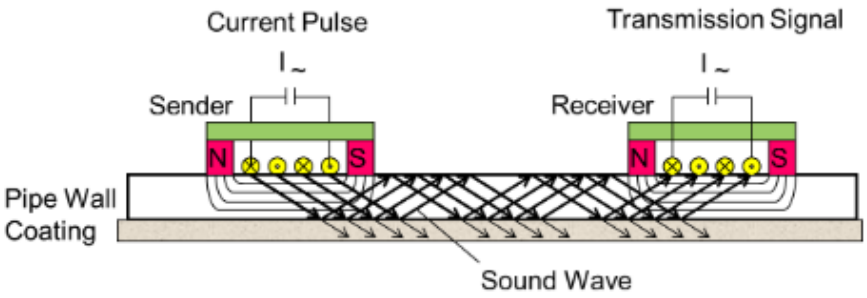


Figure 13: EMAT measuring unit [38]

EMAT systems for rail inspection are currently in the development phase and therefore hardly available on the market. In Europe, the RIFLEX project making an effort to advance its development and create an EMAT rail detection system, which enables measuring speeds of over 70mph.[39]

Advantages:

- It is a proactive system
- Faults can be detected inside the Rail
- Higher speeds than ultrasonic testing

Disadvantages:

- The EMAT system is in development phase

5.7 LDR (Light Dependent Resistor) and LED (Light Emitting Diodes) System

This system was developed with the aim of creating a favorable alternative to existing broken rail detecting systems. In order to move the LED-LDR system autonomously, it is mounted on a robot wagon. On this vehicle is the LED on one side of the rail, the LDR on the other side. If the robot moves over the track, the rail interrupts the IR rays from the LED and no IR rays can reach the LDR. Thus, the electrical resistance of the LDR is high, and no error signal is generated. If, on the other hand, a rail break occurs, the LDR receives the IR rays from the LED, the resistance decreases and an electrical signal is generated which is evaluated as a rail break. This robot also has a GPS and GSM module, which makes it possible to locate the rail break and send an alarm [40].
However, such a measuring device could only detect clearly separated rails and could potentially ignore a large number of frequent rail breaks.

Advantages:

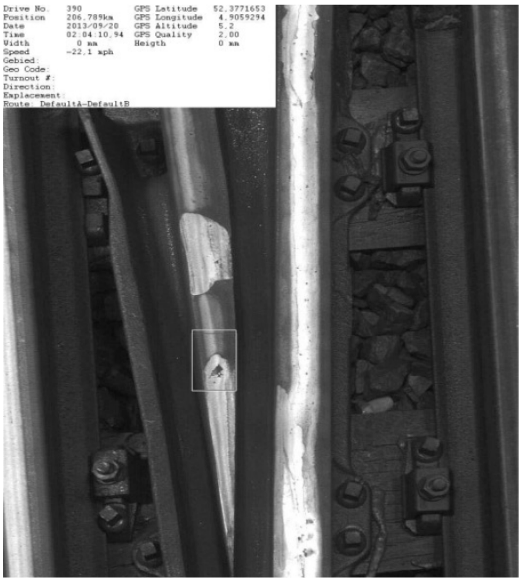
- It is a simple system
- Compact and easy to transport

Disadvantages:

- It is a reactive system
- Could only detect clearly separated rails
- Possibly problems may arise during track installations as well as turnouts

5.8 Video

By high-resolution video recording from a measuring train, it is possible to recognize the rail condition (Figure 14). These recordings are primarily used to identify head checks and loose parts on the track. Due to the high video quality, fine cracks are also recognizable and also rail breaks can be detected. However, the biggest challenge this technique is the evaluation stage, where a qualified personnel and large amount of time are demanded [3], [41].



```
Drive No.     390            GPS Latitude    52.3771653
Position      206.789km      GPS Longitude    4.9059294
Date          2013/09/20     GPS Altitude     5.2
Time          02:04:10.94    GPS Quality      2.00
Width           0 mm         Heigth           0 mm
Speed         -22.1 mph
Gebied:
Geo Code:
Turnout #:
Direction:
Emplacement:
Route: DefaultA-DefaultB
```

Figure 14: High definition video for fault detection [41]

Advantages:

- Faults can be detected with high-resolution images
- No speed limitation during recording

Disadvantages:

- For precise interpretation of the pictures and accurate evaluation specialist there is a demand of qualified staff.

6 Technologies – both track and vehicle mounted at the same time

6.1 Track circuits coupled with radio frequency technology for information transmission

This system is based on track circuits. In contrast to conventional rail break detection by track circuits, the detection unit is located on the rail vehicles. The mode of operation is based on the fact that the voltage in the rail, generated by track circuits, is detected by a sensor in the rail vehicle. If the track currents are interrupted, this will be detected by sensors on the vehicle that triggers alarm. However, only completely separated rails can be detected since these interrupt the current flow. RF unit is also accommodated in the vehicle, thereby it is possible to send alarm message to the responsible authority. The driver is also warned in time to initiate braking [42].

Advantages:

- Existing track circuits, which do not have rail break detection, could be upgraded by this system

Disadvantages:

- The System requires track circuits
- Possibly problems with insulated joints, because they interrupt the currents

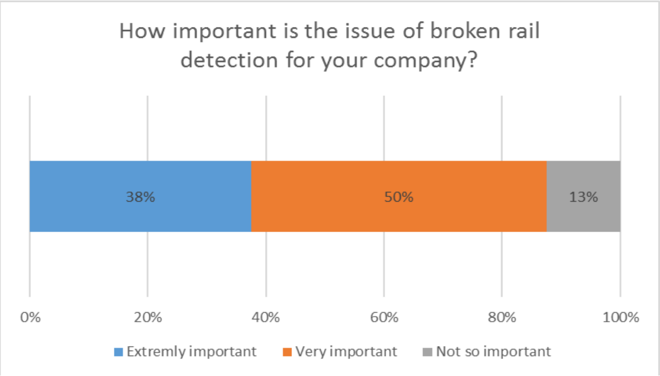
7 Stakeholders

As part of the project WP1, a survey was conducted by sending questionnaires to UIC member - European railway companies. The purpose of the survey was to find out how serious the issue of broken rail in their company is, the level of accidents that their company experienced due to broken rail. If they are currently using any kind of technology for broken rail detection, their awareness about exiting technologies as well as the strength or weakness of those technologies they might know. the survey also included questions such as the causes of rail breakage that the companies mostly experiencing including the length and the density of the railway network they are operating. Eight companies responded to the questionnaires, those are: ADIF (Spain), CFL (Luxemburg), DB Netz AG (Germany), INFRABEL (Belgium), MÁV Zrt. (Hungary), ÖBB (Austria), SNCF Réseau (France), Trafikverket (Sweden).

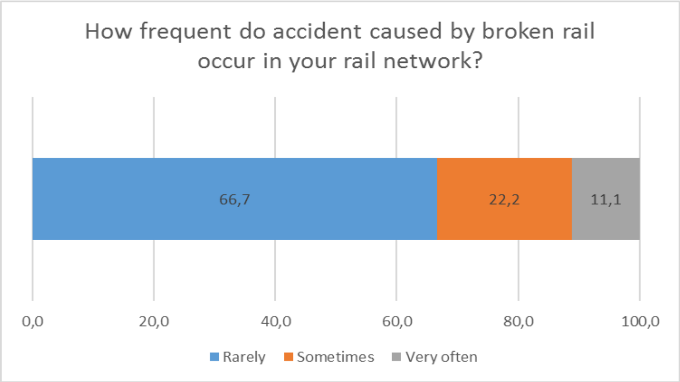
The responses to each question were evaluated and illustrated in the following section.

7.1 Questionnaires and results

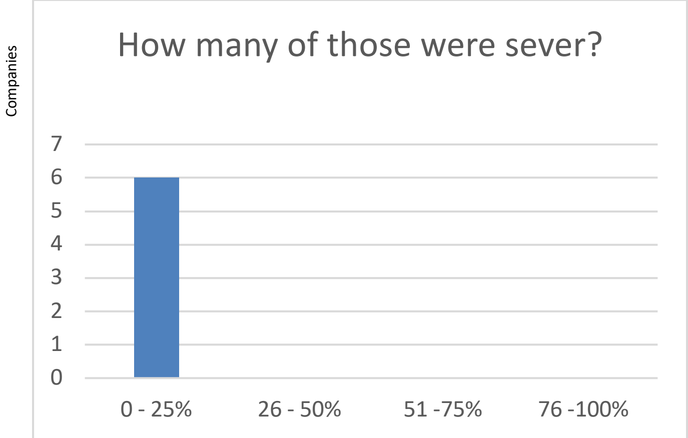
- How important is the issue of broken rail detection for your company?



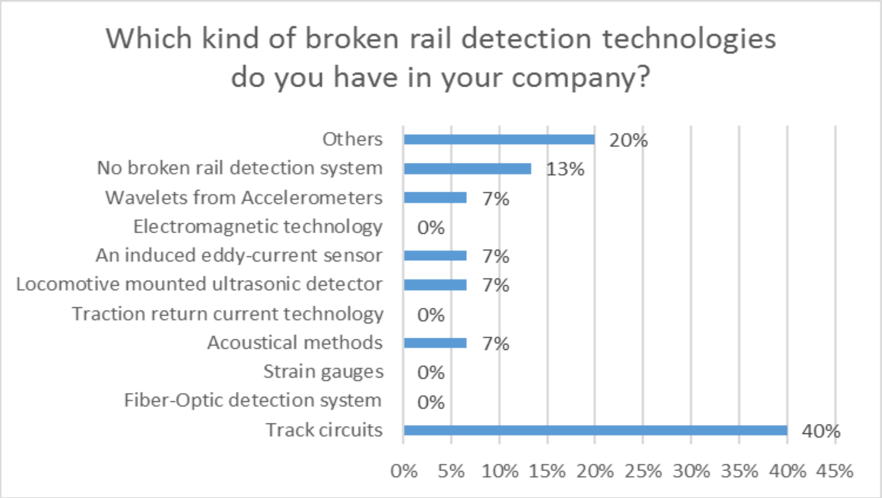
- How frequent do accidents caused by broken rail occur in your rail network?



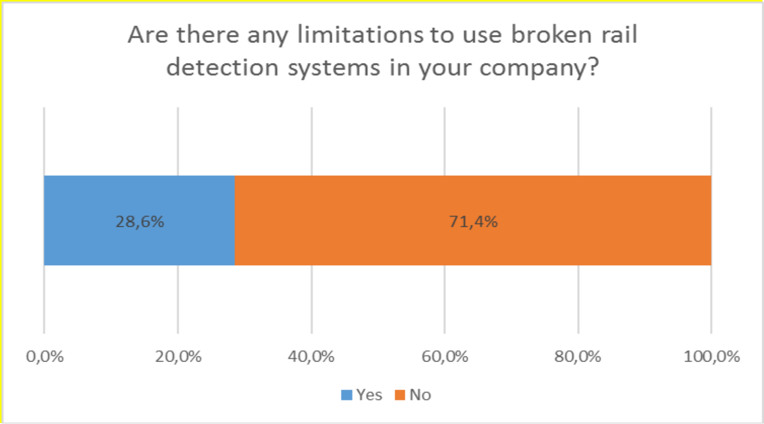
- If your company experienced accidents due to broken rails, how many of those were sever?



- Which kind of broken rail detection technologies do you have in your company?

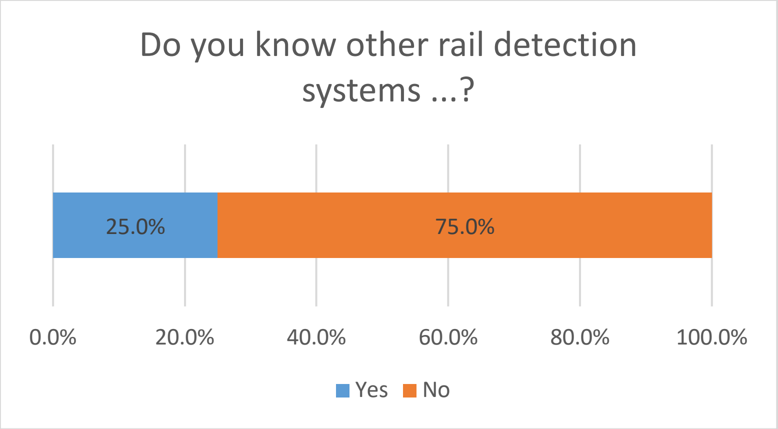


- Are there any limitations to use broken rail detection systems in your company?



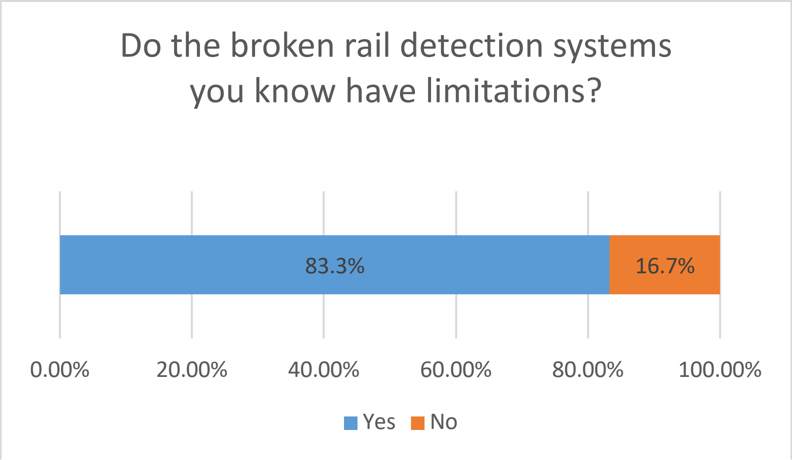
- If yes, would you please mention them?
    - In station area’s where the speed is < 60 km/h, the secondary’s tracks
    - Track circuits only in one rail. Otherwise we rely on drivers to report and that the ultrasonic testing picks them up before rail breaks

- Do you know broken rail detection systems other than track circuit based used by other railway companies in your country or internationally?



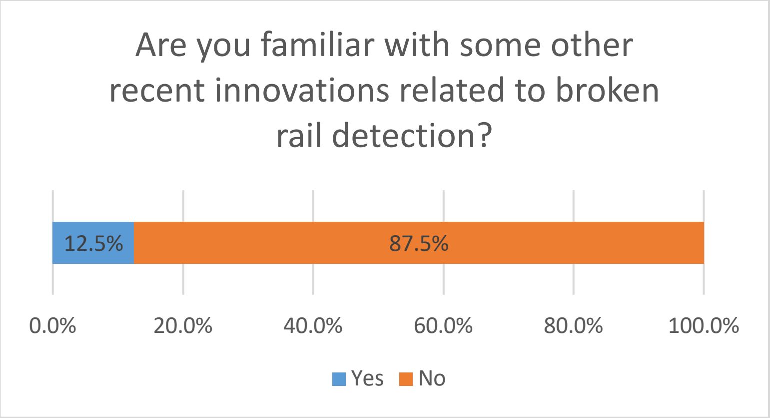
- If yes, which kind of systems?
    - Ultrasonic Testing Train
    - Rail sonic detector (from South Africa)
    - Eddy current sensor (from United Kingdom)
    - Eddy current sensor (from Germany)

- Do the broken rail detection systems you know have limitations?



- If yes, what are the common limitation?
    - Detection range
    - Not 100% effective in switches and crossing, not effective if current can pass through the break (current have to be interrupted)
    - Rail breaks can only be found when the train is testing on track
    - The rail must be complete broken

- Are you familiar with some other recent innovations related to broken rail detection?



- If yes, would you please mention them?
    - Fibre optic and ultra-sonic

- How many potential rail defects (cracking) are pre-detected every year?

Approximately 250 rail defects per year	ADIV	Spain
Usually a little less than 2000 ultrasonic defects (class 1 - to be removed) every year.	Trafikverket	Sweden
2517 with action needed / 4427 all defects	MÁV Zrt.	Hungary
Including all categories of cracking defect (very small to almost a break) we detect around 30 000 new cracks every year.	SNCF Réseau	France
Average: 50 defects in the track and 35 defects in the switches and crossings (it means defects which have to be eliminated with a deadline)	CFL	Luxemburg
2000	INFRABEL	Belgium

- How are the broken rails mainly detected (e.g. rail detection system, train driver, track worker,…)?

Track circuits, Ultrasonic inspection mounted on vehicles or trolleys detection	ADIV	Spain
positioning system (track circuit) - 20 train drivers - 6 track workers - 21 Derailment - 1 other/unknown - 26 (probably many more from train drivers in this post, but reporting is unclear)	Trafikverket	Sweden
train driver, track worker, Railroad circuits, Ultrasonic Testing Trains	ÖBB	Austria
Track worker, train driver, staff of signalling and block system	MÁV Zrt.	Hungary
By train drivers and track workers at their usual work/inspection, but I have to write something: We do not have any system to detect broken rails itself but we do spend a lot of time and work in rail inspection (visual, ultrasonic, eddy current) to find defects which would break a rail. So in my opinion we do not need a detection system because of our inspection system.	DB Netz AG	Germany
track circuit : 70 % human visual inspection : 13% train driver: 6% others: 11 %	SNCF Réseau	France
By train drivers	CFL	Luxemburg
Track circuit	INFRABEL	Belgium

- How are the rail defects mainly pre-detected (e.g. Ultrasonic, Laser, Video,…)?

Ultrasonic Inspection	ADIV	Spain
Ultrasonic testing.	Trafikverket	Sweden
Ultrasonic and Eddy current	ÖBB	Austria
Ultrasonic	MÁV Zrt.	Hungary
visual, ultrasonic, eddy current	DB Netz AG	Germany
55 % US 45 % visual (patrol men)	SNCF Réseau	France
By Ultrasonic (train for the tracks and by hand in the crossings and switches)	CFL	Luxemburg
Ultrasonic	INFRABEL	Belgium

- What are the mainly causes of the broken rail in your company? (Welding, Environment, Fatigue, ….)

Welding 20% Environment 35% Fatigue 30% On S&C's 10% Other 5%	ADIV	Spain
Fatigue	Trafikverket	Sweden
Welding, Environment / Weather	MÁV Zrt.	Hungary
Fatigue and wear	DB Netz AG	Germany
1 : Aluminium-thermic weld 2: Corrosion 3 : Squats 4: flash butt weld (mainly electric weld with manganese frog)	SNCF Réseau	France
Welding's, but the mainly causes of defects are surface damages	CFL	Luxemburg
Not a good welding method (aluminothermy welding), return current on DC line in the level crossing, environment UIC code 254 and 421	INFRABEL	Belgium

- How long is the railway network in your country?

High speed lines: 3,144 km Conventional lines: 12,241 km	ADIV	Spain
14 127 km	Trafikverket	Sweden
Track length about 5000 km, line length about 10000 km	ÖBB	Austria
about 7700 km	MÁV Zrt.	Hungary
about 60500 km of track	DB Netz AG	Germany
50 000 km of track <-> 100 000 km of rails	SNCF Réseau	France
450 km main track	CFL	Luxemburg
3607 km of lines	INFRABEL	Belgium

- How is the traffic on your network (in trains per km)?

I found one value: 13 300 000 km of traffic in the month of March 2014.	Trafikverket	Sweden
about 13144 tpkm p.a.	MÁV Zrt.	Hungary
530 E6 train-km	SNCF Réseau	France
7.800.000 trains.km/year	CFL	Luxemburg
1,15 trains/km (in 2015, 4160 trains a day)	INFRABEL	Belgium

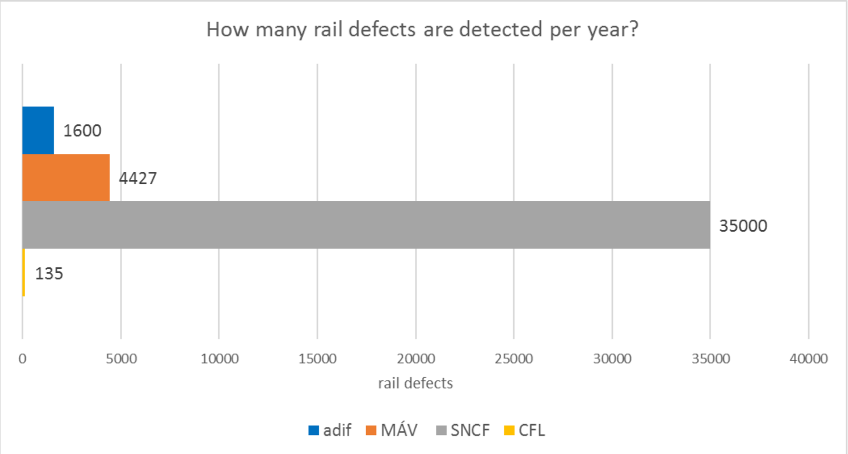
- Do you have any further suggestions, comments or concerns?

We do not have any system to detect broken rails itself but we do spend a lot of time and work in rail inspection (visual, ultrasonic, eddy current) to find defects which would break a rail. So in my opinion we do not need a detection system because of our inspection system.	DB Netz AG	Germany
my expectation for an ideal rail break detection system: • instantaneous detection and • effective in plain track and in	SNCF Réseau	France

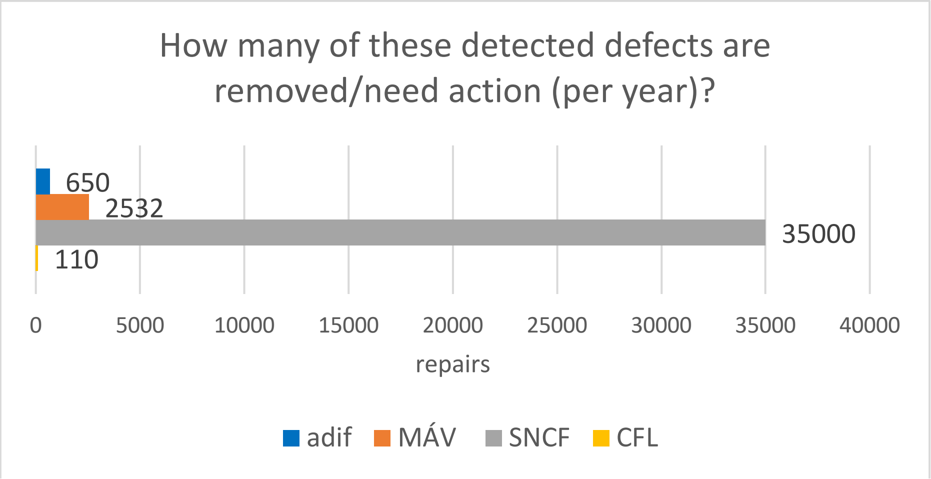
special devices (crossings, switches, switch blade, mobile frog, etc.) • localisation of the rail break • reliable and easy to maintain • immediate consequences on the signalization and transmission to the patrol men • Que le système soit fiable et maintenable		
To avoid defects, every new welding gets controlled manually with the US-device. The rails of the main tracks are controlled two times a year with the US-train	CFL	Luxemburg

8 Further questions, answered by CFL, SNCF, MÁV and adif.

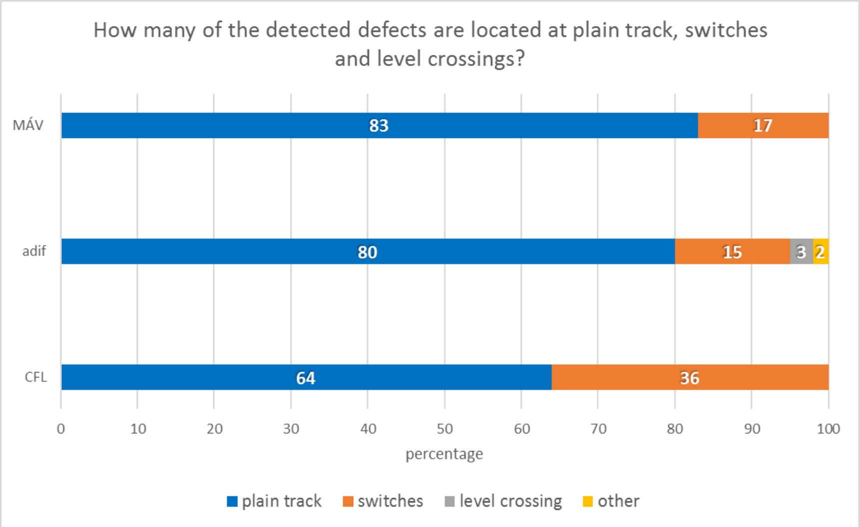
8.1 How many rail defects are detected per year?



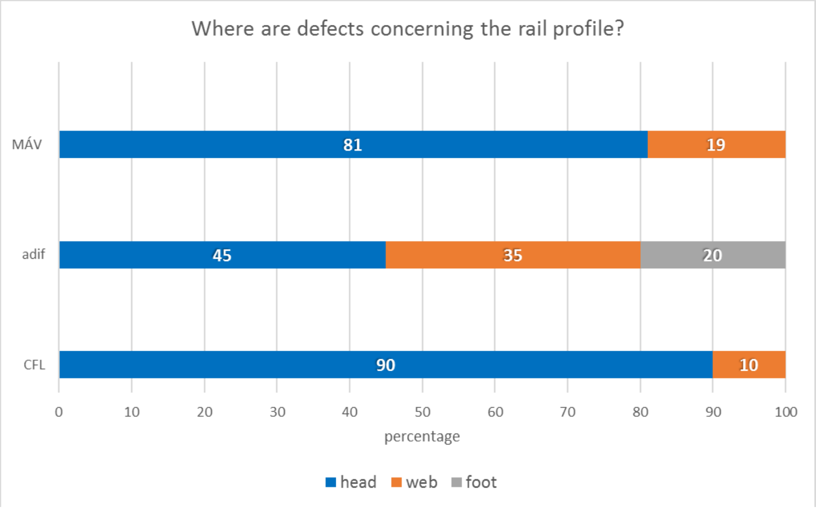
8.2 How many of these defects are removed/need action (per year)?



8.3 How many of detected defects are located at plain track, switches and level crossings?



8.4 Where are defects concerning the rail profile?



9 References

[1] M. Antoni, ‘Broken rail Detection: French experiences in broken rail detection.’, presented at the 3rd Group Meeting, Vienna, Austria, 13-Dec-2016.

[2] N. A. of Engineering, *Accident Precursor Analysis and Management: Reducing Technological Risk Through Diligence*. National Academies Press, 2004.

[3] F. Auer, ‘Multi-function track recording cars’, *Railw. Tech. Rev.*, vol. 3, no. 4, 2013.

[4] R. Cervero, *Transit-oriented development in the United States: Experiences, challenges, and prospects*, vol. 102. Transportation Research Board, 2004.

[5] M. D. Holcomb and W. D. Mauger, ‘Feasibility Study of Fiber-Optic Technology for Broken Rail Detection’, U.S. Department of Transportation: Federal Railroad Administration, Office of Research and Development Washington, DC 20590, Washington D.C., Technical Report DOT/FRA/ORD-13/44, Oct. 2013.

[6] X. W. Ye, Y. H. Su, and J. P. Han, ‘Structural Health Monitoring of Civil Infrastructure Using Optical Fiber Sensing Technology: A Comprehensive Review’, *Sci. World J.*, vol. 2014, p. e652329, Jul. 2014.

[7] G. Kouroussis, C. Caucheteur, D. Kinet, G. Alexandrou, O. Verlinden, and V. Moeyaert, ‘Review of Trackside Monitoring Solutions: From Strain Gages to Optical Fibre Sensors’, *Sensors*, vol. 15, no. 8, pp. 20115–20139, Aug. 2015.

[8] M. L. Filograno *et al.*, ‘Real-Time Monitoring of Railway Traffic Using Fiber Bragg Grating Sensors’, *IEEE Sens. J.*, vol. 12, no. 1, pp. 85–92, Jan. 2012.

[9] R. Büttner, ‘Vergleich Brillouin basierender Temperatur- und Dehnungsmessung mittels Reflexions- und Analysierverfahren’, Hochschule für Telekommunikation Leipzig, Leipzig (D), Paper.

[10] ‘Sensors | Free Full-Text | Impact Wave Monitoring in Soil Using a Dynamic Fiber Sensor Based on Stimulated Brillouin Scattering’. [Online]. Available: http://www.mdpi.com/1424-8220/15/4/8163The. [Accessed: 23-Feb-2017].

[11] R. Engelbrecht, *Nichtlineare Faseroptik: Grundlagen und Anwendungsbeispiele*. Springer-Verlag, 2015.

[12] K. Singh, C. Minto, and A. Godfrey, ‘OptaSense distributed acoustic sensing (DAS) system for the power network ??? integrated SMART-sensing real time monitoring’, in *IET International Conference on Resilience of Transmission and Distribution Networks (RTDN) 2015*, 2015, pp. 1–4.

[13] A. S. GmbH, ‘DAS / DVS (Distributed Acoustic / Vibration Sensing’. [Online]. Available: https://www.apsensing.com/de/technologie/das-dvs-distributed-acoustic-vibration-sensing/. [Accessed: 07-Mar-2017].

[14] C. Haberland *et al.*, ‘Trends in seismologischer Instrumentierung’, *System*, vol. 6, p. 1, 2016.

[15] ‘Oil and Gas’. [Online]. Available: https://www.qinetiq.com/markets/infrastructure-and-utilities/Pages/oil-and-gas.aspx. [Accessed: 07-Mar-2017].

[16] R. Cervero, *Transit-oriented development in the United States: Experiences, challenges, and prospects*, vol. 102. Transportation Research Board, 2004.

[17] ‘Real-time failure mode detection for the rail industry.’ [Online]. Available: http://www.lbfoster-salientsystems.com/. [Accessed: 21-Mar-2017].

[18] D. F. Thurston, ‘Risk Based Broken Rail Detection on Railways’, in *ASME Proceedings | Signal and Train Control Engineering*, Colorado Springs, Colorado, USA, 2014, p. JRC2014–3702, V001T03A001; 6 pages.

[19] ‘Track-Related Research: Volume 1: Broken rail Detection, Cotrol of Wheel/Rail Friction, Wide-gap Weidling Techniques. A compendium of Three Reports on Joint Track-Related

Research with the Association of American Railroads/Transportation Technology Center, Inc.' .

[20] P. LOVEDAY, D. RAMATLO, and F. BURGER, 'Monitoring of Rail Track Using Guided Wave Ultrasound'.

[21] K. Schwartz and B. A. R. T. District, 'Development of an acoustic broken rail detection system', *Final Rep. High-Speed Rail IDEA Proj.*, vol. 42, 2004.

[22] K. Schwartz and B. A. R. T. District, 'Development of an acoustic broken rail detection system', *Final Rep. High-Speed Rail IDEA Proj.*, vol. 42, 2004.

[23] 'Elastic Wave Analysis for Broken rail detection'. [Online]. Available: http://www.ndt.net/article/wcndt00/papers/idn270/idn270.htm. [Accessed: 20-Mar-2017].

[24] H. Brad, 'A Wavelet-Based Rail Surface Defect Prediction and Detection Algorithm', Doctor of Philosophy In Mechanical Engineering, Virgin ia Polytechnic Institute and State University, Blacksburg, VA, 2012.

[25] H. Brad, 'A Wavelet-Based Rail Surface Defect Prediction and Detection Algorithm', Doctor of Philosophy In Mechanical Engineering, Virgin ia Polytechnic Institute and State University, Blacksburg, VA, 2012.

[26] B. Slovák, 'Fahrzeugseitige Schienenbrucherkennung, Nachweis der prinzipiellen Machbarkeit mittels Auswertung von Beschleunigungssignalen am Achslager eines U-Bahnfahrzeuges.', TU Berlin, 2013.

[27] S. Turner and W. Y. Guernsey, 'Feasibility of locomotive-mounted broken rail detection', *Transp. Res. Board Final Rep. High Speed Rail IDEA Proj.*, vol. 38, 2004.

[28] 'CCS TSI - ccs-tsi-de-annex.pdf', 22-Oct-2006. [Online]. Available: https://web.archive.org/web/20061022214029/http:/ec.europa.eu/transport/rail/interoperability/doc/ccs-tsi-de-annex.pdf. [Accessed: 14-Mar-2017].

[29] 'MÁV Központi Felépítményvizsgáló Kft.' [Online]. Available: http://www.mavkfv.hu/index.php?lngchg=en&f=sindiagnosztika_sds. [Accessed: 14-Mar-2017].

[30] 'Ultrasonic Rail Flaw Detection | Rail Technology International'. [Online]. Available: http://www.rti-group.com/. [Accessed: 14-Mar-2017].

[31] Z. Song, T. Yamada, H. Shitara, and Y. Takemura, 'Detection of Damage and Crack in Railhead by Using Eddy Current Testing', *J. Electromagn. Anal. Appl.*, vol. 03, no. 12, pp. 546–550, 2011.

[32] 'Measurement Systems in Quality', *APB Consultant*. [Online]. Available: http://isoconsultantpune.com/measurement-systems-in-quality/. [Accessed: 15-Mar-2017].

[33] H. Dey, H. Hintze, and J. Reinhardt, 'Operation of Railway Maintenance Machines with Integrated Eddy Current Technique–An Overview of the New Requirements in Germany', in *Proceedings of the 11th European Conference on Non-Destructive Testing, Prague, Czech Republic*, 2014.

[34] Z. Chen, J. Xuan, P. Wang, H. Wang, and G. Tian, 'Simulation on high speed rail magnetic flux leakage inspection', in *2011 IEEE International Instrumentation and Measurement Technology Conference*, 2011, pp. 1–5.

[35] U.S. Department of Transportation, Ed., 'Track Inspector Rail Defect Reference Manual', 2015.

[36] 'MFL and PEC Tools for Plant Inspection'. [Online]. Available: http://www.ndt.net/article/ecndt98/pipeline/283/283.htm. [Accessed: 16-Mar-2017].

[37] Y. Xie, S. Rodriguez, W. Zhang, Z. Liu, and W. Yin, 'Simulation of an Electromagnetic Acoustic Transducer Array by using Analytical method and FDTD', *J. Sens.*, vol. 2016, p. 10, 2015.

[38] 'ROSEN - EMAT'. [Online]. Available: http://www.rosen-group.com/global/company/explore/we-can/technologies/measurement/emat.html. [Accessed: 16-Mar-2017].

[39] 'European Commission : CORDIS : News and Events : A New Rapid Automated Railhead Inspection System'. [Online]. Available: http://cordis.europa.eu/news/rcn/134576_en.html. [Accessed: 20-Mar-2017].

[40] A. Vanimiredd and D. A. Kumari, 'Automatic broken track detection using LED-LDR assembly', *Int. J. Eng. Trends Technol. IJETT-Vol. Issue7-July*, 2013.

[41] Strukton Rail, 'Video Inspection , an introduction'. [Online]. Available: http://www.struktonrail.com/.

[42] R. Sireesha, A. Kumar, G. Mallikarjunaiah, and B. Kumar, 'Broken Rail Detection System using RF Technology'.