Capacity for Rail

Towards an affordable, resilient, innovative and high-capacity European Railway System for 2030/2050

Monitoring-based Deterioration Prediction

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Deliverable 41.2

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1 EXECUTIVE SUMMARY

This report sets out from the state-of-the-art charting of current railway monitoring practices presented in Deliverable D4.1.1– "Critical components and systems – current and future monitoring". In the current report, existing maintenance practices are contrasted to which the key parameters are that affect safety, reliability, efficiency and environmental impact in different parts of the railway system. These parameters that govern the performance of a railway are then investigated in terms of whether monitoring exists or is even possible. In cases where direct monitoring is not realistic, possibilities for indirect monitoring are explored.

In this manner the report establishes what should be the true aim of any monitoring strategies – quantify the parameters that affect the performance – at the same time as the challenges of such an aim are detailed. The objective with such an investigation is to establish the required body of knowledge that is required to derive any strategy of enhancing monitoring activities. More to the point, the report provides the information on which the targets of such an enhanced strategy should be. It indicates the related complications and the benefits of monitoring of these parameters. This knowledge can then be employed to estimate the benefits of the enhanced monitoring. These benefits can then be contrasted to costs of introducing the enhanced monitoring (while addressing the complications outlined in this report). An outline of such a cost–benefit analysis will be reported in Deliverable D4.1.3.

The content of the current report is divided into sections that focus on different areas of monitoring. After a brief outline of the background, objectives and scopes, a brief review of the main findings in D4.1.1 is presented. This is followed by chapter where details are presented regarding on monitoring of vehicles and wheel/rail interaction, the status of the railway corridor, track condition, support and structures, signalling systems, and catenary and power supply.

It can be noted that the investigation revealed the major heterogeneity in monitoring purposes, use, maturity and challenges between the different areas. The purposes vary from essentially pure safety checks (e.g. regarding trespassing) to intricate analyses in order to predict future maintenance needs (e.g. regarding rail degradation). The use of monitoring varies from very common and frequent (e.g. track geometry measurements) to essentially non-existing (e.g. measurement of sleeper support conditions and monitoring of many detailed measures). The maturity varies from areas where there are mature solutions (e.g. measurement of catenary position) to areas where any existing solutions are in fairly early stages (e.g. image analysis systems to detect cracks). The challenges vary from parameters that are (at least in principle) very easy to monitor (e.g. missing fastenings), to parameters that are essentially impossible to measure directly (e.g. contact stress distribution in the wheel/rail interface).

Finally it can be noted that current monitoring strategies often target indirect measures that are compiled to give overview quality indicators. A simple (and common) example is track geometry where measures of different (global and local) track geometry are combined to a “quality index”. As outlined in the report the reality is far more complex. By the enhanced knowledge of the actual key parameters it should be possible both to better target (existing and upcoming) monitoring techniques towards the “truly influential” measures, but also to utilise simulations to better interpret and employ the existing monitoring data.

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3 ABBREVIATIONS AND ACRONYMS

Abbreviation / Acronym	Description
AC	Alternating Current
DC	Direct Current
ERTMS	European Railway Traffic Management System
ETCS	European Train Control System
KPI	Key Performance Indicators
MBO	Management by Objectives
OCL	Overhead Contact Line system
OOR	Out of Roundness
D-RAIL	EU Project "Development of the future Rail freight system to reduce the occurrences and Impact of derailment" (01/10/2011 – 30/09/2014)
HRMS	UIC project "Harmonisation – Running behaviour and noise on Measurement Sites" (31/03/2012 – 31/12/2013)
In2Rail	EU Project "Innovative Intelligent Rail" (01/05/2015 – 30/04/2018)
INNOTRACK	EU Project "Innovative Track Systems" (01/09/2006 – 31/08/2009)
RIVAS	EU Project "Railway Induced Vibration Abatement Solutions" (01/01/2011 – 31/12/2013)
OG	OLTIS GROUP AS
REFER	Infraestruturas de Portugal
TRV	Trafikverket
UPorto	University of Porto, Portugal

4 BACKGROUND

This Deliverable D4.1.2 relates to Task 4.1.2 in the Capacity4Rail Description of Work. The task sets out from the charting of monitoring that was carried out in Task 4.1.1 and deals with suitable monitoring strategies. It should already at the onset be noted that "monitoring" is used very broadly and any distinction between "monitoring" and "inspection" is often discarded. The reason for this is to avoid overly long discussions on definitions and distinctions when they do not gain the overall purpose of the report.

To further put this Deliverable in context, it can be noted that WP4.1 consists of three Deliverables. In simplistic terms D4.1.1 relates to which monitoring procedures that are currently employed around Europe. That description is heavily based on the operational experience from the partners in the WP. A brief recapitulation of some of the more important findings from D4.1.1 is provided in chapter 6.

The current Deliverable D4.1.2 essentially takes a step back and asks the question: If we could monitor everything, what would we really want to monitor to be able to assess the current status of the railway, to predict the future deterioration of the railway, to be able to identify potential issues, to be able to better plan maintenance and inspection etc. To this end, the starting point is not so much what is available (or achievable), but rather an identification of which parameters that are crucial in assessing and influencing current and future status of the track.

Naturally the real world imposes limits on what is practically (for physical, economical, safety *etc* reasons) possible to monitor. The current Deliverable addresses this issue to some extent. However, the main investigation of what is realistically possible in future railway monitoring will be reported in Deliverable D4.1.3. Here the topic is investigated through reflecting current practices (D4.1.1) to the "utopian" scenario outlined in the current Deliverable.

In this context, the current deliverable focuses on high profile monitoring tasks related to key components and systems. These are identified and a refined study is carried out to target fundamental monitoring issues such as:

- Which parameters are related to a fully functional operation, and which parameters are governing deterioration of the identified key components and systems
- What are suitable status indicators and how can functional operation, and progressive deterioration of the selected components / systems be modelled
- How can measureable data be translated to the identified parameters in different types of models (safety models, asset management models, deterioration models *etc*).

Here it is important to note that many parameters in predictive models (e.g. wheel/rail contact patch size) cannot (currently) be directly measured. The study will identify such parameters and also provide frameworks for condition monitoring and asset management in a shorter and longer perspective (as governed by the complexity of data gathering and modelling).

It is also important to appreciate that monitoring have very different possibilities and objectives for different application areas. This is especially obvious in the case of a railway where monitoring of signalling system, the electrical system, the track construction *etc* pose very different demands and also relate to very different core objectives. For this reason, the different chapters in this Deliverable are (even though efforts have been made to harmonize) different in layout and scope of content.

5 OBJECTIVES AND SCOPE

As mentioned in chapter 4, key objectives were to identify:

- Which parameters are related to a fully functional operation, and which parameters are governing deterioration of the identified key components and systems
- What are suitable status indicators and how can functional operation, and progressive deterioration of the selected components / systems be modelled
- How can measureable data be translated to the identified parameters in different types of models (safety models, asset management models, deterioration models *etc*).

To provide a simple illustration of "key parameters" and "measurable data", one can study the case of an elasticity modulus of a material. The elasticity modulus is employed in a number of models that are used to predict the behaviour of components built from the material. It can therefore in many respects be considered as a "key parameter" of the material. However, the elasticity modulus cannot be directly measured. Instead we can measure for example the elongation of a bar of a certain cross-section loaded by a certain force. Using such "measurable data" we can deduce (using standard methods from solid mechanics) the elasticity modulus of the material.

As also mentioned, the objectives vary between different subsystems of the railway. Some additional objectives for the different chapters are

CHAPTER 7: MONITORING STATUS OF VEHICLES AND WHEEL/RAIL INTERACTION

Here objectives are essentially two-fold: The main objective is to assure that the vehicles are safe to operate on the line and do not pose risk of introducing operational disturbances or impose a too severe environmental footprint (e.g. through noise emissions).

A second objective is to use this track based monitoring of vehicles to aid operators and train owners in their operations and maintenance efforts (either for free or through a fee-based information exchange).

Since these two objectives are to a fairly high extent interlinked, there has been no clear distinction between them. Solely operational aspects such as monitoring of time keeping and wagon localisation (unless the objective is to identify a malfunctioning wagon) have however been excluded.

Note that wagons deteriorate over time, and the monitoring data discussed can be used to characterise and predict such trends. This topic is however left fairly open since it is mainly related to the operators' asset management and relies also on maintenance information that is possible to gain only from workshops (i.e. typically not available to the infrastructure manager).

CHAPTER 8: MONITORING OF RAILWAY CORRIDOR

The two objectives with this type of monitoring that have been addressed in this Deliverable is to ensure that the load gauge is free from obstacles and that there are no (unauthorised) persons (or larger animals) in the track. The objective is of course to ensure safe (both for trains and for the society as a whole) operations.

The conditions that are monitored typically not evolve slowly (the possible exception being vegetation growing into the load gauge). Consequently, trending becomes of less importance. On the other hand, conditions may change rapidly, which raises the question of monitoring/inspection intervals.

CHAPTER 9: MONITORING OF TRACK

The chapter is generally divided into sections based on the different components of a track. These sections then detail what the key parameters are, how they can be used to predict status and degradation, and finally how measureable parameters can be translated to the key parameters.

It may be noted that track monitoring relates both to safety and maintenance objectives (and also to environmental objectives). However, since these are often interlinked, no strict division between these is made.

CHAPTER 10: MONITORING STATUS OF SUPPORT AND STRUCTURES

Here the focus is on bridges and tunnels. The monitoring objective relates to ensuring safety, but also to ensure sufficiently good operational conditions and assist maintenance activities.

To this end the chapter outlines key parameters that should be monitored, how these parameters are monitored and currently available equipment that can be employed.

CHAPTER 11: MONITORING STATUS OF THE SIGNALLING SYSTEM

To understand monitoring of signalling systems, it is first essential to understand how the signalling systems are designed and operate. The chapter therefore sets out with an overview of the European Rail Traffic Management System and the European Train Control System in general and associated equipment in particular. The chapter highlights key features of these systems, and indicates different means of monitoring them. This concerns also the track (and vehicle) based components of the monitoring system that are influenced by progressive deterioration due to operations.

CHAPTER 12: MONITORING STATUS OF CATENARY (AND POWER SUPPLY)

The focus of the chapter is on the power supply from the contact lines into the pantograph. The chapter goes through key components and possible means to monitoring to manage these systems.

In relevant cases examples of operational systems are presented. Note that these presentations complement the overview of existing monitoring systems that was given in Deliverable D4.1.1.

6 KEY FINDINGS FROM THE SURVEY REPORTED IN D4.1.1

The current investigation sets out from the findings in Task 4.1.1: Critical components and systems – current and future monitoring. In brief, the key findings are summarized in the following:

The report D4.1.1 gives an overview of possibilities to avoid failures and defects in the infrastructure by using available technologies able to monitor the “health” of components and systems. The high safety standard in railways today is based on an inspection strategy – in some countries in fixed time intervals, in other countries (semi)-condition-based. The common understanding of the infrastructure managers (IM) is that the economics of maintenance must be improved to be competitive towards road/water/air transports. In this respect, the incident recovery through real-time data management is an essential part of maintenance, which can be ensured by advanced monitoring and non-intrusive inspection.

The identification of the top components, which are most expensive in maintenance or traffic interruptions/delays, is a suitable starting point for the development of monitoring systems. The identified critical components in railway infrastructure are:

- Infrastructure components: switches, signalling/interlocking, weak embankments, insufficient drainage *etc*.
- Critical parts of the network: critical nodes/bottlenecks, heavily loaded/operated track sections
- Vehicles as a critical component (motivates the need for Wayside Train Monitoring Systems)
- People and/or the human factor
- IT infrastructure and its critical parts

As an overall approach is quite rare (or at least not published) in the European railway sector, the deliverable D4.1.1 presents a holistic approach focussed on switches and crossings considered as most critical components in the infrastructure due to their major impact on the maintenance quality.

Furthermore, some new concepts and developments of monitoring, that have been established recently are referred to. One of those new concepts is a monitoring system based on acoustic measurement that implies a concept of collecting measurement data regarding rail traffic noise and rail related noise respectively, by means of permanent measuring stations, which is described in detail. The second concept employs monitoring by in-service trains (implemented on the ICE train, and carried out on two selected passenger lines at the DB network) in order to monitor the track. The measurement system measures the accelerations of the axle bearings during the normal train operation. Based on these measurement data, the longitudinal level of the track is identified.

Additionally, noticeable switch and crossings can be identified with related parameters to quantify their condition. The results are transferred by mobile communications to a central server and provided to the asset manager through weekly reports. The data can be used as asset condition data and transformed to actual and forecast usage information. In addition, D4.1.1 outlines monitoring systems applied for detecting critical areas and structure, train weight and load imbalances of trains, wheel profiles, vehicle curving, traction and braking performance.

The report gives an overview of which technologies that are available today and that can be introduced within a short timeframe into the network. However, it also highlights difficulties of a migration strategy, since all solutions need their own infrastructure for energy supply and data transmission. In this context it should also be noted that the first products resulting from the latest innovation programs funded by the EC have now come to the market. These are smaller, cheaper, less energy consuming and WiFi/GSM compatible.

Another, often underestimated, problem is the diagnosis platform and the assessment of measured monitor data. Because this topic is very often strongly connected to company IT policies, it was not a focus of the report.

Reflecting on the needs of IM, the targets for the developments in the C4R-Project are described. A major requirement when considering future monitoring solutions of switches and crossings is that they should provide additional information regarding the frog-performance, e.g. forces and noise level during wheel passages. The additional requirements are: low cost, user-friendly, maintenance free. The key success of such monitoring technologies lies in the low costs, low consumption (currently supported by batteries but the trend is towards energy harvesting) and their easy and rapid installation during construction or maintenance of the infrastructure. They must further be oriented towards a cost-effective, easy and rapid sensor (including batteries) replacement and/or maintenance. The data should be able to be processed into diagnostic information so that failure prevention and a reliable maintenance forecast can be done. The benefits of monitoring systems can only be realised if failures are anticipated and performance of each asset type (degradation models) can be predicted, based on gathered real-time data and processing tools.

In order to establish the base for an efficient use of the monitoring systems further steps are necessary for investigation of non-intrusive innovative monitoring techniques, like the definition of the functional and technical requirements, the technical and economic evaluation of monitoring solutions and the meaningful context of the technologies. In this context it should be noted that the whole monitoring strategy must be a part of the business case “infrastructure management”.

7 MONITORING STATUS OF VEHICLES AND WHEEL/RAIL INTERACTION

This chapter deals with key parameters of vehicle characteristics. The sections of the chapter are selected to reflect different aspects in which the vehicles influence the track.

Note that the focus of the chapter is on the vehicle–track interaction. In addition, the vehicles also interact with the signalling system (through different interfaces) and with the power system (through the pantograph/catenary interaction, and the wheel–rail grounding). These interactions will be dealt with in chapters 11 and 12, respectively.

The chapter deals with monitoring that is motivated for safety, maintenance and environmental reasons. Regarding the connection to safety, the topics discussed here can be put in context by providing a brief overview of the EC funded project D-RAIL, and the UIC funded project HRMS. In D-RAIL the most important causes of (freight) derailments were identified and the corresponding key safety related parameters identified. Note that in this context "safety related" implies parameters related to causing a significant increase in the probability of derailment. However even if the safety limits defined in HRMS are exceeded, derailment will only occur in combination with other factors being at their worst. Finally, even if a vehicle derails, the probability of injuries and casualties is limited. All these factors combine to make train travel on the order of 50–100 times safer than road travel[1].

Regarding status of vehicles, the key derailment mechanisms identified where[2, 3]

- Axle failures, which can further be divided into
    - Breakdown of bearing boxes, which will be explicitly discussed explicitly below.
    - Mechanical fatigue of the axle. The key parameters here are load levels (which will be discussed below and also in section 8), and mechanical damage to the axle. Monitoring of mechanical damage to the axle is deemed outside the scope of the report – it is on the limit since track-based monitoring equipment can be used (at least in theory) to identify mechanical damage on the free surfaces of the axle, it can however not be used to identify damage in the wheel/axle assembly (mainly stemming from fretting[4]).

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[1] B Åkesson: SIKAs data och ökad säkerhet för persontransporter (in Swedish), 3 pp, 2010

[2] D-RAIL, Deliverable D3.2: Analysis and mitigation of derailment, assessment and commercial impact, 283 pp + annex 18 pp, 2013

[3] D-RAIL, Deliverable D3.3: Guidelines on derailment analysis and prevention, 38 pp, 2013

[4] A Ekberg: Fretting fatigue of railway axles – a review of predictive methods and an outline of a finite element model, *IMechE Journal of Rail and Rapid Transit*, vol 218, pp 299–316, 2004

- Flange climbing where the main influencing factors are track geometry (as discussed in section 8), wheel and rail profiles (as partly discussed in section 9), load imbalance (as discussed below) and vehicle suspension characteristics (as deemed outside the scope of the report).
- Rail breaks – here the key influencing factors (fairly) generally are impact loads (as discussed below), vehicle characteristics such as axle spacing and speed (which to some extent is discussed below), track characteristics such as track stiffness (discussed in section 8), and rail cracks (as discussed in section 9). In addition, severe wear (as discussed in section 9) may also have an effect[5].
- Wheel failures, where the safety related types can be divided into
    - Initiation from thermal overloading as discussed explicitly below.
    - Subsurface rolling contact fatigue where the main influencing parameters are vertical load magnitudes (as discussed below), contact geometry (discussed to some extent in section 9) and material defect size in the wheel rim (deemed outside the scope of the report)[6].
    - Disc failures where the main influencing parameters are material defects (deemed outside the scope of the report) and wheel–rail forces (discussed below and in section 8).

One of the main conclusions from the D-RAIL project was that half of derailments (and 75% of costs) could be handled by three types of inspection / monitoring equipment, namely hot wheel and axle box detectors, axle load checkpoints, and track geometry measurements.

In HRMS the topic was taken further by aiming at specifying harmonized measurement stations for wheel/rail contact forces and noise emissions. This resulted in a deepened analysis aimed at identifying key parameters (as is explored further below). It also highlighted the importance of vehicle identification, a topic that – although very important – is deemed outside the scope of the current report.

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[5] E Magel, Peter Mutton, A Ekberg and A Kapoor: Rolling contact fatigue, wear and broken rail derailments, *Proceedings of the 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs, Colorado, USA, 11 pp, 2015

[6] A Ekberg, E Kabo and H Andersson: An engineering model for prediction of rolling contact fatigue of railway wheels, *Fatigue & Fracture of Engineering Materials & Structures*, vol 25, no 10, pp 899–909, 2002

7.1 NOMINAL VERTICAL LOAD CHARACTERISTICS

This section relates to parameters that give an overview of the operational loading of the track. Such parameters are mainly useful for maintenance purposes (in contrast to safety related measures, see section 7.2). The most important parameters include

- Operational frequency of the track
    - number of axles
    - number of trains
- Net loading of the track
    - (quasi-)static wheel load
    - (quasi-)static axle load
    - (quasi-)static bogie load
    - total loads per wagons and trains
    - load per linear metre of the track

These data do not give much information about the current status of the track or the vehicles. However, they are critical in estimating deterioration rates, planning maintenance actions *etc*. Further they are the basis for assigning track access charges.

An interesting issue here is how to deal with overloading that can be identified by comparing the net loading towards the allowed loading of the line. This issue was investigated in the UIC HRMS project and is discussed in the final report of that project[7].

7.2 IMPACT LOADS AND LOAD IMBALANCES

7.2.1 KEY PARAMETERS

7.2.1.1 IMPACT LOADS

Impact load magnitude is a key parameter when it comes to the risk of rail breaks. However regarding rail crack growth they are of less importance[8] (with the possible exception of wheels with

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[7] UIC, HRMS: Harmonization – Running behaviour and noise on measurement sites, 153 pp, 2014

[8] J Sandström and A Ekberg, Predicting crack growth and risks of rail breaks due to wheel flat impacts in heavy haul operations, *IMechE Journal of Rail and Rapid Transit*, vol 223, no 2, pp 153–161, 2009

out-of-roundness of a higher order). This is due to the relative rareness of high impact loads and that these have to occur in a limited section of the rail to have any major effect on an existing crack.

Regarding impact loads, it has been shown[9] that (at least) the following load parameters have a significant influence on causing a rail break:

- Impact load magnitude
- Time evolution of impact load – time for loading, time for off-loading and time of potential lack of contact
- Impact position (in relation to (sleeper) support, and in relation to existing rail cracks.

Note that the impact position in relation to sleeper position and any existing crack will vary with every wheel (flat) impact and thus not possible to account for more than in a "worst-scenario" manner.

When it comes to the influence of causing wheel disc failures, it has also been shown[10] that there is an influence of the lateral position (on the wheel tread) of the impact load.

7.2.1.2 LOAD IMBALANCES

Regarding the risk of derailment due to flange climbing, it has been shown[11] that the risk of derailment is influenced by the lateral and longitudinal imbalance within a wagon. In addition, a skewed wagon frame will have a significant effect on the risk of derailment.

In the HRMS-project it was shown that the best correlation between (numerically predicted) derailment and measures of load imbalances was obtained for a combination of axial imbalance (load on left/right wheel on one axle) and longitudinal imbalance (load on first bogie/second bogie on one wagon). In addition, a skewed bogie frame can be identified from the diagonal imbalance (right wheels on front and left wheels on second / left wheels on front and right wheels on second wagon).

The different load imbalances are defined in Figure 1. Note that the derailment criteria are derived for freight wagons (or rather for wagons with two bogies, each of which contains four wheels). For other configurations (e.g. Jacobs bogies) the situation may become more complicated.

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[9] J C O Nielsen, E Kabo and A Ekberg, Alarm limits for wheel–rail impact loads – part 1: rail bending moments generated by wheel flats, Chalmers Applied Mechanics, Research report 2009:02, 35 pp, 2009

[10] D-RAIL, Deliverable D3.2: Analysis and mitigation of derailment, assessment and commercial impact, 283 pp + annex 18 pp, 2013

[11] *ibidem*

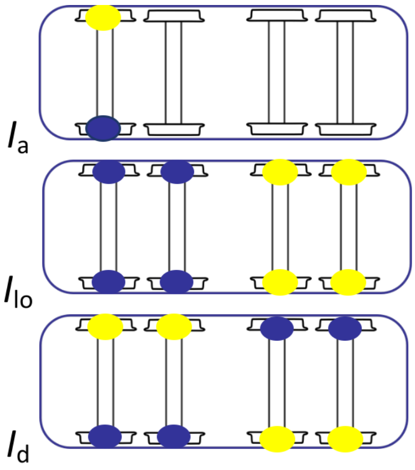


Figure 1 Definition of axial, longitudinal and diagonal load imbalance

For this reason, a sensible approach would be to consider that, the key parameters regarding flange climb derailments are

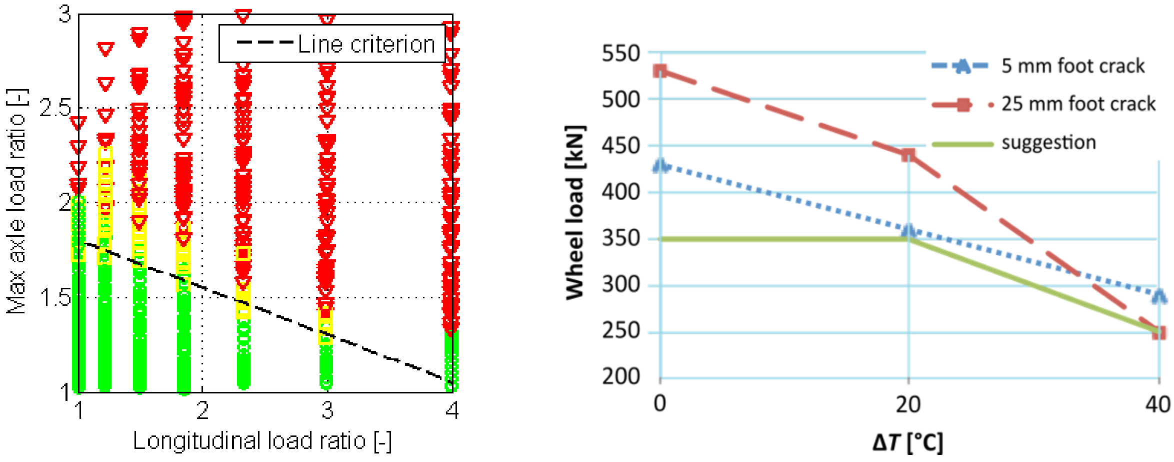
- All (average) wheel loads (with their pertinent location logged)
- Indication of which wheels that contain to the same bogies and the same wagon.

7.2.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

Safety monitoring is currently somewhat special when it comes to status indicators in that it is basically a binary indicator: Either the system is safe (meaning below a safety limit) or unsafe (meaning above a safety limit). The current trend is that this is slowly progressing towards a more holistic approach where it is also considered that trains that are stopped in track cause operational disturbances. These tend to shift traffic to road. Since road traffic is some two orders of magnitude less safe than rail this is not a good safety procedure from a holistic perspective. Consequently, there is a drive to impose safety levels that can be employed while minimizing operational disturbances (e.g. by allowing trains to proceed to the next station).

In an extension improved and extended monitoring also allows for refined risk analyses: As an example if there are unusually many impact loads just below the safety limit, this imposes a higher risk for rail breaks than normal since the risk of rail breaks is also related to the occurrence of rail defects which has uncertainties. Consequently, such a situation might impose additional rail inspections and/or requests to the operators for more thorough inspection of their wheels.

However, currently the first step is to improve the existing safety limits. Here D-RAIL and HRMS came up with suggested limits for load imbalance and rail breaks, see Figure 2.



a) b)

Figure 2 a) Suggested limit for load imbalance[12], b) Suggested alarm limit for wheel impact loads where Δ*T* is the deviation from stress free temperature (positive when below)[13]

Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of additional parameters that are required if the monitoring data should be useful and mitigating activities efficient. These include

- Direction of transit
- Operational speed
- Wheel configuration data (on which wagon, which bogie, which axle, which side)
- Train ID (to identify operator *etc*)

7.2.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

- Impact load magnitude

The load magnitude needs to be measured indirectly e.g. from acceleration or strain. Here it is crucial that the measurements are properly calibrated, have a suitable and specified resolution in time (i.e. can account for the high frequency load content), and can account for impact loads at least along a distance corresponding to the circumference of the largest wheel operating on the line. It must also

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[12] UIC, HRMS: Harmonization – Running behaviour and noise on measurement sites, 153 pp, 2014

[13] A Ekberg, E Kabo and J C O Nielsen: Allowable wheel loads, crack sizes and inspection intervals to prevent rail breaks, *Proceedings of the 11th International Heavy Haul Association Conference (IHHA 2015)*, Perth, Australia, pp 30–38, 2015

be able to account for impact positions distributed over a reasonable lateral distance across the railhead.

- Time evolution of impact load – time for loading, time for off-loading and time of potential lack of contact

This information is more complicated to make practical use of. Typically, a "worst-case" scenario is employed. However, it would not be unrealistic to actually account for the time evolution when assessing the severity of a wheel flat. Consequently, it would be beneficial if the monitoring equipment could store the entire time history for potential future use.

In addition to these parameters it must be noted that the measurement section should be representative to reflect a "bad case scenario" of the line. This generally implies that vehicles are passing at the highest line speed. Other influencing factors such as track stiffness can be accounted for by correction factors[14].

- All (average) wheel loads (with their pertinent location logged)

This should not pose any major problems even though (as for impact loads) the loads have to be indirectly measured.

- Indication of which wheels that contain to the same bogies and the same wagon.

This demand implicitly requires RFID tagging (or similar) of wagons (with cross-referencing to vehicle database) or bogies.

As for the "book keeping data" this should be readily available information with the exception of speed, which may require additional sensors to record.

7.3 VEHICLE CURVING, TRACTION AND BRAKING PERFORMANCE

7.3.1 KEY PARAMETERS

Curving, traction and braking will give rise to frictional stresses and relative motions between wheel and rail. Depending on the characteristics, this may result in[15] wear, (thermal and/or mechanical) crack formation *etc*.

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[14] J C O Nielsen, E Kabo and A Ekberg: Alarm limits for wheel–rail impact loads – part 1: rail bending moments generated by wheel flats, Chalmers Applied Mechanics, Research report 2009:02, 35 pp, 2009

[15] A Ekberg, B Åkesson and E Kabo: Wheel/rail rolling contact fatigue – Probe, predict, prevent, *Wear*, vol 314, nos 1–2, pp 2-12, 2013

In addition poor curving may cause high track shift forces that will deteriorate the track geometry. Analogously, braking (and to a less extent traction) may cause a longitudinal shift of the rail that may e.g. promote sun kink formation (if compressing the rail) or rail breaks (if elongating the rail).

The key parameters behind these phenomena are the longitudinal and lateral track forces induced by the vehicle on the rail. Mainly the magnitude, but also the time evolution is important. In addition the damage phenomena relate also to the relative slip between the wheel and the rail, the geometry of the wheel and the rail, and the material characteristics. These parameters will be considered further below (in relation to the wagons mainly in section 7.4).

Operation of towed railway vehicles is usually associated with how the vehicle behaves in the transition between speed limits or during running through reverse curves. That is why simulation tasks for vehicle behaviour on long distance runs simulation are formed this way as well. Simulation algorithms do not define some deviations of operational characteristics; neither for the vehicles, nor infrastructure. This primarily concerns specific defects on running gears of vehicles, and also track geometry.

7.3.1.1 WAGON MODEL DESCRIPTION AND FORMULATION

A railway car composes from running gear – that is equipment used to carry traction on the track. Brake is also a part of running gears. Running gear is connected to the underside of a vehicle by a mass of elastic springs and dampers.

The underside is for transferring longitudinal forces being applied on the vehicle, carrying the body, and fixating the running gear. The assembly of the underside includes the vehicle's framework itself (in case of standalone designs the body and the framework may blend), and buffering and coupling gears.

The body is used as a space for persons or goods. Special cars have a purpose-built tool placed on it.

Kinematics of the car is for the purpose of simulation then calculated as a function of varying velocity of a moving object in real time. Details of the simulation model are not featured in this document, but there is a link to a publication[16].

7.3.1.2 EXTENDED FORMULATION FOR DEFECTIVE TRACKS

Projecting of track geometry (TG) in the Czech Republic follows standard ČSN 73 6360-1:2008 Konstrukční a geometrické uspořádání koleje železničních drah a její prostorová poloha – Část 1: Projektování (Alignment design of railway track and its spatial position - Part 1: Design, in Czech), which is binding on the basis of enactment of provision of the Ministry of Transportation no.

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[16] J Dvořák, B Šulc: Simulace radiálního polohování železničního dvojkolí (Simulation of the radial positioning of the railway wheel, in Czech), Czech Technical University in Prague, *Proceedings MATLAB 2002*, 7 pp, 2002, dsp.vscht.cz/konference_matlab/matlab02/sulc_dvorak.pdf

177/1995 Sb, which issues construction a technological regulations of the railway. For the purpose of simulation models, to fulfil the requirements for safety, passenger comfort, and operational sustainability in relation to preventing needless restrictions resulting utility parameters of the track (especially line speed), the base irregularities in TG are:

- Unbalanced superelevation
- Sudden change in the unbalanced superelevation
- Directional alignment of the track
- Relative mutual position of superelevation ramps and switches
- Precluding of dangerous clinching of bumpers

Other tracked things include impacts of deviations during separate TG parameters on running of the vehicle, especially:

- Track gauge and its changes – as track gauge increases, the value of difference of real radiuses of opposing circles on the inside and outside wheel of the wheelset and striking angle of the guiding wheelset increases, which leads to emergence of overlaps of individual wheels of wheelsets connected to a solid axle. This occurrence results in slipping waves on the surface of the stretch of rails with negative impacts on requirements of the designed and operational state of track geometry in relation to mutual forces between the vehicle and the track, wearing of rail stretches, transfer of vibrations to the superstructure, and noise pollution increase.
- Track direction – effect of deviations of the track's direction can have undesirable effects on the safety in relation to derailment.
- Distortion of the track – it is a key parameter of evaluated quality of TG, because these defects often take part in the causes of vehicle derailment. Derailment caused by a distortion of the track happens because of axle wheel weight transfer and following climbing of the axle onto the top of the rail.

7.3.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

The most straightforward status indicators are the longitudinal and lateral wheel–rail contact forces. As mentioned above these should be coupled with data on wheel and rail profiles if a detailed evaluation is to be performed.

An indirect status indicator of the curving characteristics would be the evolution of track geometry in curves (related to lateral forces), the evolution of rail profiles in curves (related to curving forces, wheel/rail slip and profiles of wheels and rails), and the occurrence and characteristics of cracks in rails.

An indirect status indicator for longitudinal forces would be the evolution of stress free temperatures in rails.

Balanced Scorecard (BSC) is a system for management and measuring of performance of an organisation. It is based on lying down a balanced system of interlinked performance indicators. The Balanced Scoreboard method is universally applicable in all sectors.
BCS works with four perspectives of evaluating of an organisation:

- Financial perspective
- Customer perspective
- Process perspective
- Learning and growing

Each area has set

- Objectives
- KPI (Key Performance Indicators)
- MBO (Management by Objectives)

Goals in an organisations tie together with its mission and formed vision. Properly set goals fulfil the conditions and principles of SMART (they are specific, measurable, achievable, realistic, and time-specific). Achieving of measurable goals is measured and verified using **indicators** or metrics.

KPIs, similarly to goals, should fulfil SMART conditions.

SMART is an analytical technique for proposing goals in management and planning. It is an acronym of initials of goal attributes:

S – Specific

M – Measurable

A – Achievable/Acceptable

R – Realistic/Relevant

T – Time Specific/Trackable

7.3.2.1 OVERVIEW OF PREDICTION ALGORITHMS

An overview about the used algorithms is briefly described as follows.

Association Rules

Data mining – Data mining can be defined as a “nontrivial acquiring of previously unknown and potentially useful information hidden in data”. With its help, we try to gain more complex and useful information from stored data than graphs and basic overviews. From statistical point of view, this is about investigating mutual relationships or patterns in data. Its purpose is to analyse data contingencies, define trends, and, if the data type allows, predict future development. Use in practice is quite wide especially in fields where large amount of data is collected. Typical examples of huge data sets are:

- client data,
- communication data,
- movement of users on the Internet (applicable in IoT),
- course of operational parameters (in industry and transportation).

Tasks, which stand above the data itself, can be divided into several groups:

- Classification – classification methods
- Aggregation/Segmentation
- Prediction
- Regression
- Association rules

Typical methods, which fall under data mining, are classification and regression trees, neuron networks, and machine learning methods.

Fuzzy logic

Fuzzy Logic was initiated in 1965 at the University of California in Berkeley. Fuzzy logic is a technology, which allows machines/devices to tell how a performed activity is going using sensor and adjust its work cycle accordingly as per the results. Use of this system was allowed by precise sensors, e.g. temperature, liquid level, water contamination, *etc*, in conjunction with control microprocessors.

Considering that in machines/devices controlled by a processor programs are saved in the memory as a sequence of functions and decision algorithms, these devices can allow simple updating of their programs once better and more efficient ones are developed. Thus they can always keep up with the development.

Artificial Neural Network

Use of MATLAB Neural Network Toolbox is directed at complementing of a modelling tool/software MATLAB for designing, visualisation, and simulation of neuron networks. It provides complete support and also graphical interface, which helps especially in monitoring. Use is possible for example in assessing durability of components of some machines and devices, which allows predicting length of the life cycle of e.g. vehicles.

Decision Tree

When designing a decision tree, the method "divide and conquer" is used. Training data is gradually separated into smaller and smaller subsets (tree nodes) so that these subsets are dominated by examples of a single class. This approach is often called "top down induction of decision trees"(TDIDT), which is an algorithm:

1. Choose a single attribute as a root of a subtree,
2. Distribute data in this node into subsets according to values of selected attribute and add node for each subset,
3. If there is a node in which the data do not belong to the same class, repeat the procedure in step 1, otherwise end.

7.3.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

Longitudinal wheel/rail forces are notoriously difficult to measure, especially from vehicles. Further, there is a need to measure these where they occur. To some extent these locations can be deduced (e.g. in to, and out from stations). However it would be difficult to get an overall picture. Also indirect measurements of the stress free temperature evolution in the rail are currently very cumbersome. A technically possible way of monitoring would be to collect the control data from trains operating the line. Obviously there would however be massive challenges in adopting such a system.

Monitoring of curving characteristics has more potential. Lateral wheel–rail contact forces are possible to measure. Here the challenge is more related to providing a fair comparison between different vehicles: To induce lateral forces requires a curving design that imposes underbalanced conditions. The response of a vehicle will then be very depending on the characteristics of such a curve (including not the least the adopted rail profile). As for indirect measurement through track geometry degradation together with evaluation of wear and crack growth rates, these are already employed around Europe. However, a systematic coupling to vehicle characteristics is very seldom performed. Further, such a coupling will also be more qualitative than quantitative.

Detected data is electronically gathered and logged directly in the hard drive of a PC in the basic unit on the track. From there, the data is transmitted into evaluation unit with a screen and a printer, which is located near the station master. He/she is responsible especially for alert states, hand-filling train numbers and in case of an eventual identified defect assure an operational measure (stopping the train (immediately or after reaching a station). Diagnostics results are being used for on-line monitoring of select failure states of railway vehicles (alert/alarm). Station master and dispatcher, who then ensure stopping and eventually taking the wagon out of the train (decoupling), are informed about serious above-threshold problems. Then, the wagon keeper is informed and will later secure the repairs.

The main benefit at this time seems to be provision of local operational alerts at indicative places after defects had developed to a level that they affect safety performance.

Figure 3 Configuration of the monitoring data equipment

7.3.3.1 DATA IDENTIFICATION

Identification of data and its assigning to specific railway wagons is one of important requirements for the following processing of data coming from diagnostic systems on railway. Current practice using assigning an ordinal number of the axle from start to end of the train for further processing is not enough. There are various devices for identification of trains on the move, for example:

- Optical
- Radio (RFID) – passive or active

Their purpose is capturing of identification data on the vehicle and pairing them to the measured data about defects on the vehicle.

Optical systems work on the principle of capturing images of passing trains and following analysis and searching for identification marks.

Radio systems work with identifier (tags), which are placed on vehicles and contain coded information about the train number, type, weight, *etc*. The reader placed next to the track is able to read this data when the train passes through its action radius.

Passive tags receive energy from the reader antenna located next to the rails and return a signal containing the coded data. Active tags include a miniature battery, which powers a signal emitter as the train rides by a reader.

7.3.3.2 LINKS TO HIGHER INFORMATION SYSTEMS

Information about the technical state of railway vehicles, which provide the installed systems, lead to creation of new identification links: train – wagon with problem code – infrastructure manager – railway undertaking (wagon keeper, *etc*).

Data gathered in the field are thus again transmitted to the central server, where they're only assigned identification (specific train, or alternatively specific wagon). This algorithm of identification, A.K.A. "pairing with a train", results from time-space incidence of a train on a communication with an indicator and uses time and space consecution of events on a train recorded in the central system.

Identification of a specific wagon is done by an algorithm of assigning wagon number based on mandatory information of the railway undertaking about so called train composition (see TAF TSI "Train Composition Message"). This information defines a set of trains in a train, including its order, so it also enables derivation of specific wagon's number.

The information system provides a data interface for other systems in the form of a web service. Diagnostics server collects data from diagnostic indicators distributed across the infrastructure. The goal is data exchange between both systems.

The information system provides data interface for other systems by the means of a web service. The diagnostic server collects data from diagnostic indicators distributed across the infrastructure. The goal is an exchange of data between both systems. Data from the diagnostic server about measured values on the diagnostic indicator located on infrastructure are transferred into central system application.

And conversely, data on current train composition in the location of an indicator, including unique identification of a train (TTID), are transferred from the central application to the diagnostic server.

Currently none of the systems use predictive logic described above to generate development of a possible event on the basis of measured values. There is insufficient information for this step; particularly there is a high risk of unexpected development leading to an accident, which is not allowed by used process diagrams in CSMs (Common Safety Methods). Then, after a thorough process analysis in line with CSM, it is possible to make a step towards transformation of measurable data into key parameters.

7.3.4 MEASUREMENT OF DYNAMIC BEHAVIOUR OF TRAINS

The dynamic behaviour measurements (vehicle reaction measurement) are an essential part of commissioning new track lines, as well as of periodic inspection of the existing network.

However, the dynamic behaviour measurement can be considered also as a sub-task of quality control of the railway infrastructure. In that respect it supplements track geometry measurements with high-speed range by an additional safety level.

The vehicle reaction measurement is necessary in order to check the vehicle and track interaction in terms of driving safety, resultant track stress and driving behaviour considering the local speed limit.

7.3.5 KEY VALUES TO BE MEASURED, CALCULATED AND ASSESSED

By carrying out the dynamic behaviour measurements the wheel forces – lateral guiding force and wheel vertical force – are measured. Further, the sum of the lateral guiding forces, as well as standard deviation between wheels can be identified. In addition, accelerations in the bogy and in the car body (lateral and vertical) can be measured and assessed to determine the running stability of the vehicle.

It is here worth to mention, that an independent assessment scheme exists based on the expertise on dynamic behaviour tests (according to UIC 518, EN 14363, DIN 5550, EN 12299).

From the lateral guiding force and the sum of the lateral guiding forces and standard deviation, conclusions can be derived. Amongst others, in terms of existing directional errors and track leap (narrowings). From measurements of the wheel vertical forces, conclusions can be made regarding single faults in longitudinal level, twist, superelevation, and also related to rail failure and wear of track elements. Failures concerning cant height, high conicity, aligning problems, long-wave longitudinal level failures and several consecutive longitudinal level failures can be identified from acceleration values. The acceleration data can also be used to identify local differences in track stiffness and wear on track elements.

A continuous deterioration of the measured values and the corresponding deterioration in track quality can be determined through observations over several years. This requires periodic repeats of dynamic behaviour measurements throughout the track. In connection, track sections with more severe responses should be identified.

7.4 WHEEL PROFILES

The contact between rail and wheel depends on three major geometric factors.

- Wheel profile
- Rail profile
- Curve radius (and indirectly cant, speed and running characteristics of the train).

Note here that a wheel profile in itself does not provide much information; it needs to be matched to the rail profile that it is traversing. Rail profiles will be discussed in section 9.6.

In addition, the contact geometry and contact pressure distribution will depend on material characteristics (essentially the elasticity modulus, Poisson ratio and plasticity properties). The consequences of the contact will depend on additional parameters. Exactly which these are will depend on the phenomenon considered.

7.4.1 KEY PARAMETERS

Due to the fact that there are a number of different phenomena influenced by wheel profile conditions, there will be a number of key influencing parameters. To reflect this, the description below will relate to these different phenomena. These phenomena are marked in boldface below.

For **wear** a common predictive model is according to Archard[17]. Here the resulting wear volume can be expressed as

$$V_{\mathrm{wear}} = k\frac{P \times d}{H} \qquad (1)$$

where V_{wear} is the volume of wear, P is the normal force, δ is the sliding distance, H is the hardness of the softer material and k is a wear coefficient that will depend on the contacting materials, sliding speed contact pressure, *etc*. As seen, there are no geometric parameters explicitly included in equation (1). However, both sliding distance and the wear coefficient implicitly depends on the wheel and rail profiles, in particular the lateral wheel geometry. In addition, the normal force will depend on the circumferential wheel profile (*cf* section 7.2.1.1).

An alternative wear prediction model is the *T*–gamma model, which employs the product of total creep force (*T*) and total creepage (gamma). Also in this case the wheel profile geometry is not

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[17] J F Archard: Contact and rubbing of flat Surface, *Journal of Applied Physics*, vol 24, no 8, pp 981–988, 1953

explicitly related to the wear, but will be implicitly be included in both *T* and gamma, and also in the damage function that relates *T*–gamma magnitudes to wear (and surface initiated rolling contact fatigue) magnitudes.

The *T*–gamma model has also been employed for **surface initiated rolling contact fatigue**. Another approach here is based on the so-called shakedown map[18]. The shakedown approach has been extended[19] with the derivation of a "fatigue index" for surface initiated rolling contact fatigue. This index (which is the horizontal distance from WP to BC in Figure 4) can be expressed as

$$FI_{\mathrm{surf}} = f - \frac{2pabk}{3P} \qquad (2)$$

where *f* is the traction coefficient, *P* is the normal contact force (positive in compression), *a* and *b* are semi-axes of the Hertzian contact patch, and *k* the yield limit in cyclic shear.

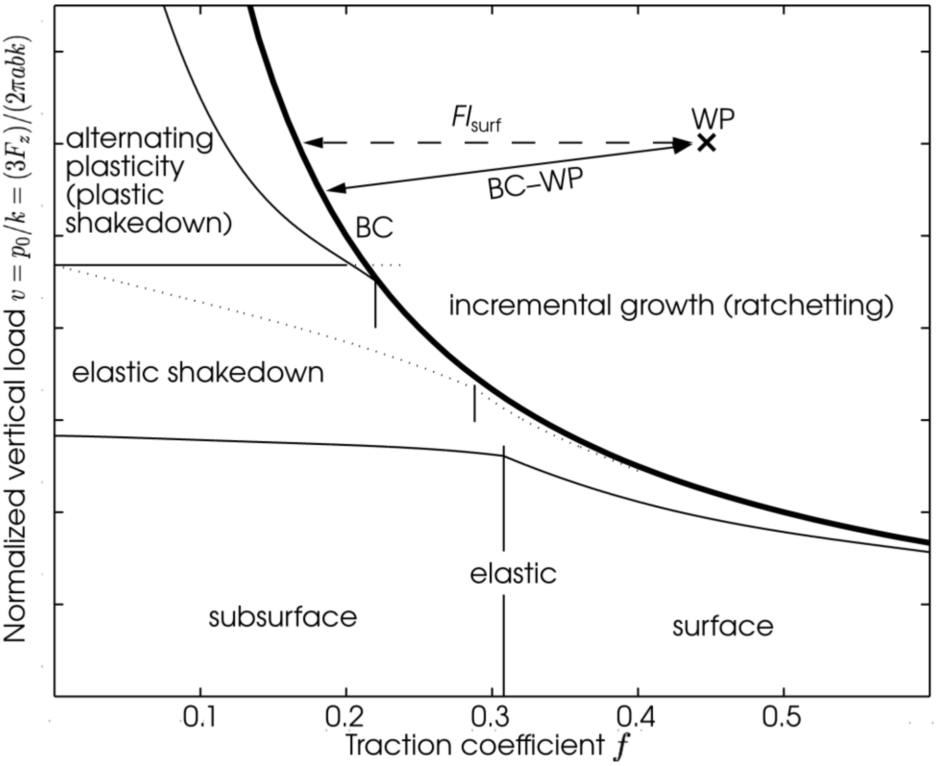

Figure 4 Shakedown map with fatigue index indicated, from [15].

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[18] K L Johnson: The strength of surfaces in rolling contact, *IMechE Journal of Mechanical Engineering Science*, vol 203, pp 151–163, 1989

[19] A Ekberg, E Kabo and H Andersson: An engineering model for prediction of rolling contact fatigue of railway wheels, *Fatigue & Fracture of Engineering Materials & Structures*, vol 25, no 10, pp 899–909, 2002

Also in this case the (lateral) wheel profile is not explicitly included, but will (through a geometric relation involving the rail profile, and the lateral position of the wheel on the rail) be implicitly included in *a* and *b*, and (through vehicle dynamics relations) in *f* and *P*.

For **subsurface initiated rolling contact fatigue**, a criterion of fatigue initiation setting out from the Dang Van multiaxial fatigue criterion can be expressed as[20]

$$FI_{\text{sub}} = \frac{F}{4\pi ab}\left(1+f^2\right)+c_{\text{dv}}\sigma_{\text{h,res}} > \tau_{\text{e,red}} \qquad (3)$$

Where *F* is the vertical contact load, c_{dv} and $\tau_{\text{e,red}}$ material parameters and $\sigma_{\text{h,res}}$ the hydrostatic part of the residual stress in the wheel or rail. Regarding the influence of the lateral wheel profile geometry, the same comments as for surface initiated RCF applies.

Of particular importance for wear and surface initiated RCF formation is the occurrence of **hollow wear** which will increase the lateral loads (and contact stresses) significantly. Even worse, an excessive hollow wear may cause instability. In practice hollow wear is often quantified by the magnitude of tread wear (or indirectly by the flange height). It has however been shown that this measure has a very poor correlation to the wear volume and the risk of surface initiated RCF[21, 22].

Flange climbing induces a risk of derailment (as discussed in section 7.2.1.2). Here the equivalent conicity between wheel and rail is the decisive geometry factor. In a thorough evaluation this would require the full wheel profile (and also other vehicle dynamics related parameters). In practice, a rough estimation of the slope of the flange (the *qR* measure) is commonly used instead.

A **thin flange** may increase the risk of flange break, which would impose a potential safety risk. To assess this risk thoroughly, the flange geometry (together with lateral loading and material characteristics including crack sizes) is required. In practice, a rough estimation of the flange thickness (*Sd*) is commonly used.

To summarize, we may conclude that:

- Wear and surface initiated rolling contact fatigue (RCF) basically depend on the full (lateral) profile of wheels, which will be required (together with rail geometries, axle load, change in speeds, track geometry *etc*) to predict creep forces, creepage, sliding distance *etc*. If creep forces could be measured (see section 7.3), this would add complimentary information.

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[20] *ibidem*

[21] R Fröhling, A Ekberg and E Kabo, 2008. The detrimental effects of hollow wear – field experiences and numerical simulations, *Wear*, vol 265, no 9, pp 1283–1291

[22] K Karttunen, E Kabo and A Ekberg: Numerical assessment of the influence of worn wheel tread geometry on rail and wheel deterioration, *Wear*, vol 317, nos 1-2, pp 77–91, 2014

- Subsurface initiated RCF will in addition depend on the circumferential wheel geometry in the sense that this will govern vertical load magnitudes.
- Hollow wheel wear is a very influential factor. In general, knowledge of the entire lateral wheel profile is required to evaluate the influence of the hollow wear.
- Flange climbing basically depends on the equivalent conicity, which in a thorough evaluation would also require the full lateral profile, but is often estimated with the slope of the flange (qR).
- To establish the influence of a thin flange, the geometry of the entire flange (and also a knowledge of acting loads and cracks in / strength of the flange material) is required.

7.4.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

Currently (see Capacity4Rail, Deliverable D4.1.1) wheel profiles are classified by the width and slope of the flange (relating to flange break and flange climbing), and also by the flange slope and possibly the thread hollow (to quantify hollow wear). These measures give indications on the safety of the profiles, but it has been shown that these measures have little to no influence of the formation of wear and RCF[23].

With the possibilities for more detailed evaluation of the wheel profile geometry that has arrived in recent years, a better approach is to evaluate the influence of the wheel geometry on the propensity for wear and RCF from the full wheel profile. As will be discussed in section 7.4.3 such a framework has been established.

7.4.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

For wear and surface initiated RCF numerical simulations will be required to translate measured wheel profile data to corresponding wear rates and RCF damage levels. Note that instead using measured lateral loads (as discussed in section 7.3) will not directly cancel the need for lateral wheel profile data since the load magnitudes do not provide any information about creepage, sliding distances and contact stress magnitudes. For the case of subsurface initiated RCF it has however been shown how this can be (partly) circumvented through employing extensive numerical simulations to establish a relation between measured load magnitudes and pertinent subsurface initiated RCF magnitudes[24].

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[23] *ibidem*

[24] E Kabo, R Enblom and A Ekberg: A simplified index for evaluating subsurface initiated rolling contact fatigue from field measurements, *Wear*, vol 271, nos 1–2, pp 120–124, 2011

A more extensive approach has been employed to directly relate measured wheel (and rail) profiles to wear and surface initiated RCF magnitudes[25, 26]. The assessment scheme features a parametrisation of the wheel (or rail) profiles and then assesses the parameterised profile through previously established meta-models. Such an assessment is very fast and allows e.g. to rank the status of curves throughout an entire line in terms of the severity of the rail profile geometries in the curves[25, 27].

7.4.3.1 EXAMPLE OF AN OPERATIONAL MONITORING SYSTEM

To measure wheel profiles, the DB project OptiPro may be mentioned as a good example. This relates to a Wayside Monitoring System measuring the wheel transversal profile of passing vehicles with high speed (160 km/h). The project was managed by the track measurement department of DB Netz. The wheel monitoring equipment is a modular configured measuring equipment consisting of a laser-based measuring system, which collects relevant data of wheelsets passing a rail frog. From the collected data conclusions can be drawn in terms of the optimized design of the crossing geometry. The wheel monitoring equipment can be regarded as a Wayside Monitoring System for measuring the geometrical dimensions of the wheel set. It measures critical dimensional parameters for maintenance[38]. Due to the position of the different elements, the system uses 2 cameras and 2 lasers for the axle (if the diameter measurement is required it is necessary to use one more laser), see Figure 5. The cameras (internal and external) capture the image as the wheel is passing by. Consequently, it is possible to capture the entire image needed for the analysis, including the inner face, which is indispensable reference for any measure.

All the information relating to each wheel goes directly to the control PC, which saves it and sends the information to the program. There an analysis of these data can be made and the corresponding reports can be generated, see Figure 6.

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[25] K Karttunnen: Influence of rail, wheel and track geometries on wheel and rail degradation, Chalmers University of Technology, PhD Thesis, 2015, ISBN: 978-91-7597-203-9

[26] K Karttunen, E Kabo and A Ekberg: Gauge corner and flange root degradation estimation from rail, wheel and track geometry, *Proceedings of the 10th International Conference on Contact Mechanics and Wear of Rail/Wheel Systems (CM2015)*, Colorado Springs, Colorado, USA, 9 pp, 2015

[27] K-J Bengtsson, E Kvarnström, C Möller and O Sundlo: Nedbrytningsmått för järnvägshjul och räl (in Swedish), Chalmers Applied Mechanics, BSc Thesis 2015:03, 29 pp (and 4 annexes 3+1+2+1 pp) http://publications.lib.chalmers.se/records/fulltext/220580/220580.pdf

Figure 5 The structure of the monitoring equipment outdoor

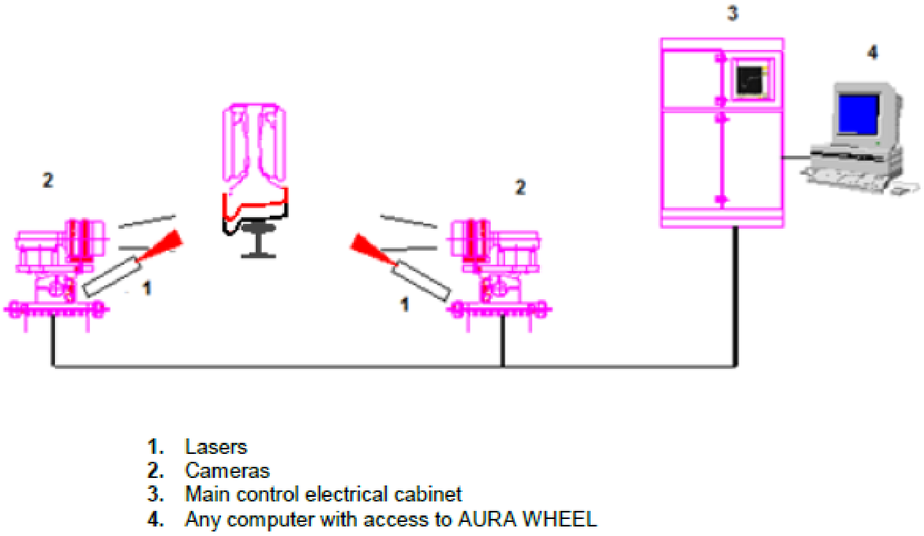
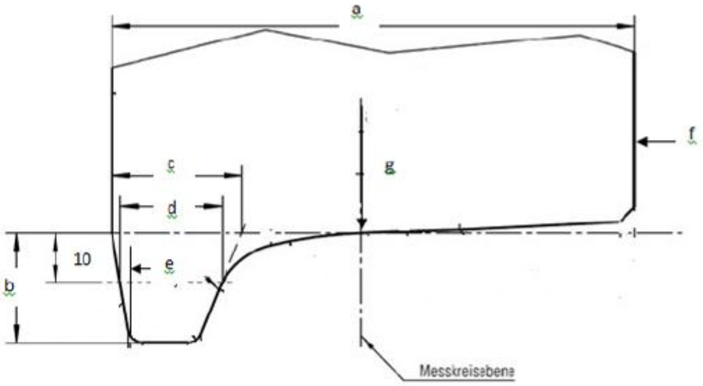


Figure 6 Description of the modules of the monitoring equipment

The wheel monitoring equipment measures, without mechanical contact, the wheel parameters of the vehicles as they pass through the installation. The parameters that are measured are shown in Figure 7: These include flange thickness and height, thickness of the external part of the wheel (to the end of life wheel mark), flange slope (Qr). Further, the diameter is calculated by measuring the thickness of the tread, using the dead end mark of the wheel tread band.

The system also supplies a parameterized reproduction of the wheel profile, which allows many other parameters to be measured. Furthermore, it allows a margin of allowance to be defined, outside of which the tread must be regenerated.



a = rim thickness
b = flange height
c = flange thickness
d = second flange thickness
e = Qr
f = back to back distance
g = diameter measured through witness groove

Figure 7 Parameters that are measured

In a first step the concerned Wayside Monitoring System was placed on the track located in Haste (between Hannover-Minden in Germany), see below Figure 8. This track section is actually used as crossing trial, since it is one of the most frequented track sections of DB network.

Since a few weak points of the monitoring system were brought to light during the first application, DB Netz has decided to redesign the construction of the monitoring equipment in order to ensure more practicality (manageability and mobility) through less weight, modular structure, less connection parts, for rapid dismantling and assembly, particularly as a demand for tamping.

In this respect the optimization of the design is mainly containing measures like lower construction of the system, more stable execution of the frame and adjustment of the internal layout on the higher vibration *etc*. After completed redesign, the monitoring equipment will be installed on the track, on the same place and will be used as a Wayside Monitoring System.

Figure 8 First application of the measuring system in Haste

Objectives of the project are:

- Measurement of operational wheel transversal profiles for optimization of the crossing geometry. So far the wheel transversal profile is measured with walking speed at DB factory premises. But this measuring system enables the measurement of wheel transversal profiles with high speed (160 km/h) through a laser-scan system embedded in the monitoring equipment. Thus there will be a better knowledge of the actual profiles operating the track and which forces the frog is exposed to.
- Demonstration of the feasibility of the wheel monitoring system on the track with high speed, aiming to extend the measuring system with wheel force detection system
- By the means of this wheel monitoring equipment all the relevant measuring data will be collected and provided for modelling, i. e. the complete wheel trajectory during the passage of the frog will be modelled and simulated. This will be the base for the optimization of the frog geometry design.

Key parameters of the measurement system:

- Wheel transversal profile
- Flange thickness, thickness of the external part of the wheel (to the end of life wheel mark)
- Height,

- flange slope Qr (see Figure 7)

Benefits:

- Reduction of wear of the frog (in particular the initial wear) through geometry better fitted to traversing wheel profiles; increase of lifetime of the wheel set and of the frog
- Wear optimized design of the wheel trajectory area and reduced maintenance efforts as well as reduced costs
- Avoiding/eliminating regular and manual measurements in the course of inspection or in the factory premises. These are linked to high efforts and costs

Results achieved so far:

- All the weak points of the systems have been identified as a base for the optimization/redesign of the monitoring equipment.
- Transmission of wheel profile data to the main computer is working. The main computer is responsible for coordinating all modules of the system, transmitting the orders necessary to capture the data, monitoring the measurements and showing the state of the remote wheel-scan at trackside.
- First quantitative evaluations show that the measurement results are in the right order of magnitude.

The next steps after the re-installation on the track will be to check and prove the winter suitability of the monitoring equipment. Moreover the wish and demand for the future is to extend the system with additional measurement system, for instance with the wheel force detection system for detecting wheel flats.

7.5 OVERHEATED WHEELS AND BREAKDOWN OF BEARING BOXES

7.5.1 KEY PARAMETERS

7.5.1.1 OVERHEATED WHEELS

The safety related consequence of overheating of a wheel is the thermal fracture of the wheel, see Figure 9. The key parameters in this process are[28]

- Thermal power into the wheel – typically due to (malfunctioning) braking
- Time of heating

The above two items relate to the heating of the wheel, both in terms of peak temperature (typically at the surface) and penetration depth into the wheel.

- Wheel material characteristics
- Size(s) of existing crack(s) in the wheel (tread).

The two items above are typically not known (and very difficult to monitor) by the infrastructure manager.

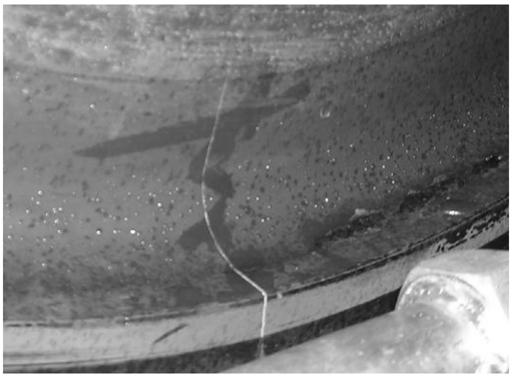


Figure 9 Thermal fracture of a railway wheel extending into the wheel disc[29].

There is also a more maintenance related consequence in that a locked wheel may cause a wheel flat, commonly with martensite formation. Key parameters in this respect are sliding distance with locked wheel, frictional characteristics (that gives the thermal power), material characteristics,

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[28] S Caprioli, T Vernersson and A Ekberg: Thermal cracking of a railway wheel tread due to tread braking – critical crack sizes and influence of repeated thermal cycles, *IMechE Journal of Rail and Rapid Transit*, vol 227, no 1, pp 10–18, 2013

[29] *ibidem*

cooling rates *etc*[30]. These parameters are better known/monitored from the operator's side. Regarding "track related monitoring", the resulting wheel flats will eventually be captured by wheel load detectors (see above) if they are sufficiently large.

7.5.1.2 BREAKDOWN OF BEARING BOXES

Breakdown of bearing boxes is a gradual (albeit sometimes very fast) process where the internal friction in the bearing increases (e.g. due to debris, lubrication breakdown *etc*). The increase in internal friction generates heat, which typically accelerates the breakdown process. Eventually the bearing breaks down completely, which typically results in a thermal fracture of the axle, see Figure 10.

Figure 10 Thermal fracture of a wheelset axle[31]

7.5.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

Apart from vehicle based (direct or indirect) monitoring of the thermal status of the wheel (which then is required to be mounted on **all** wheels), the temperature of the railway wheel can be measured from track. This is an indirect measure that aims to account for thermal power into the wheel, and the time of heating. Remote measurement of wheel temperature is inherently complicated. One reason for this is that such a measurement needs to make assumptions regarding surface characteristics of the wheel.

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[30] J Jergeus: Railway Wheel Flats. Martensite Formation, Residual Stresses, and Crack Propagation, PhD thesis, Chalmers University of Technology, Gothenburg, 1998

[31] Picture by signature BD, postvagnen.se

Also for bearing boxes the current scope of remote measuring (as opposed to fleet-wide, vehicle based monitoring) put restrictions on potential solutions. Currently monitoring is based either on bearing box temperature measurements or bearing box noise emissions. Both of these are indirect indicators of bearing box breakdown that increases the internal friction and thereby vibration levels (that lead to noise emission) and friction levels (that generate heat).

7.5.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

To the best knowledge of the authors, current translations from measured quantities to the actual status of the bearing boxes (in terms of internal friction and degradation rate) are very empirical. Due to the nature of the bearing boxes this is also likely to be a relationship that varies between manufacturers (and perhaps even between different models from the same manufacturer). One possibility to improve this would be to establish monitoring intervals (specified in terms of kilometres between detector stations) and limit values (of measured temperature and/or noise emission) and require manufacturers to ensure that the degradation rates are sufficiently slow to ensure that the bearing will be detected before failure. Needless to say, such a requirement must be Europe-wide not to limit possibilities for cross-border operations. (A version would be that the manufacturer specifies the degradation interval in terms of kilometres. This could however limit the selection of "allowed" bearing boxes depending on the detector spacing of the lines operated.)

7.6 NOISE AND VIBRATIONS

7.6.1 KEY PARAMETERS

There are several mechanisms generating railway noise and vibration. For noise, the dominant source is rolling noise generated by wheel and rail vibrations induced by surface (acoustic) roughness in the wheel/rail contact. Squeal noise is caused by a lateral excitation mechanism during curving. Aerodynamic noise becomes significant for high-speed operation, *etc*. Various generation mechanisms are listed below, see also[32] for a detailed description. Noise is emitted by vibrations from the different vehicle and track components and transmitted to the receiver by air, ground and structure (such as adjacent buildings).

NOISE GENERATION MECHANISMS

- Wheel/rail roughness (rolling noise)
- Squeal noise (top of rail)

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[32] D Thompson: Railway noise and vibration: mechanisms, modelling and means of control, First edition, Elsevier, Oxford, UK, 2009, 518 pp

- Flanging noise
- Braking noise
- Impact noise (at crossings, joints *etc*.)
- Traction noise
- Rattling (freight vehicles)
- Wind induced noise
- Aerodynamic noise induced at high speed

NOISE EMISSITTION SOURCES

- Sleeper
- Rail
- Wheel
- Vehicle body
- Pantograph and catenary
- Bridge
- Level crossings
- Crossing

MEANS OF TRANSMISSION

- Air-borne
- Ground-borne
- Structure-borne

Vibrations can be separated into contributions generated by the quasi-static, and by the dynamic vehicle-track excitation. The quasi-static excitation is due to the static component of the moving load, while the dynamic excitation is caused by wheel/rail irregularities. These are the mechanisms that are the sources of excitation due to sleeper periodicity, and to rolling noise and impact noise. The generated loads are transferred to the track and the soil, where vibrations propagate to excite the foundations of adjacent buildings[33].

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[33] G Lombaert, G Degrande, S François and D Thompson: Ground-borne vibration due to railway traffic: a review of excitation mechanisms, prediction methods and mitigation measures. In J C O Nielsen et al (editor), Noise and vibration mitigation for rail transportation systems, *Proceedings of the 11th International Workshop on Railway Noise*, Uddevalla, Sweden, 2013, pp 253–287

Wheel out-of-roundness (OOR) and unsprung mass are key railway vehicle parameters influencing the dynamic wheel-rail contact loads and inducing ground-borne vibration. For a given combination of vehicle speed, track/soil conditions and wheel/rail irregularity level, reducing the unsprung mass leads to a reduction in contact loads and vibration at frequencies above the resonance of the wheelset on the primary suspension.

For wheel–rail interface generation of vibrations, wheel out-of-roundness (and in particular local tread defects such as wheel flats) can have a strong influence on vibration magnitudes. Track geometry defects with wavelengths shorter than some 10 m have some influence on the low frequency vibration. Isolated defects shorter than 3 m may generate significantly high free-field vibrations. Finally, dipped rails at welds and insulated rail joints can generate high wheel–rail impact loads with broad frequency contents that lead to high vibration levels. Regarding track defects, longitudinal level misalignments with wavelengths of 0.6 m seem to have the highest overall vibration impact, although the highest vibration levels are typically found near welds and insulation joints. More details can be found in the summary of the main results from the RIVAS-project[34].

Based on an extensive field measurement campaign, where the influence of several different types of vehicles on vibration level was measured, it was found that freight locomotives generated the maximum vibration levels. For several freight locomotives of the same type, a high statistical variance (up to 20 dB) in measured vibration level was observed indicating a significant spread in wheel tread conditions and OOR. Early detection of out-of-round wheels and corrective wheel maintenance are important measures to reduce vibration levels. More details on work performed are available in the RIVAS report[35].

7.6.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

The characteristics of railway noise and vibration can be described by different status indicators:

- A-weighted equivalent continuous sound pressure level ($Lp_{\mathrm{Aeq},Tp}$) with T_p being the measurement time interval corresponding to the passage of the whole train, one single car or one single bogie/axle.
- Equivalent particle velocity level ($Lv_{\mathrm{eq,Tp}}$) or equivalent acceleration level ($La_{\mathrm{eq,Tp}}$) at various distances from the track. T_p is defined as above.
- Frequency content of noise and vibration evaluated in 1/3 octave bands.

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[34] UIC, RIVAS – Vibrations: Ways out of the annoyance, a summary of outcomes, 28 pp, *International Union of Railways (UIC)*, 2013

[35] J C O Nielsen et al: Reducing train-induced ground-borne vibration by vehicle design and maintenance, *International Journal of Rail Transportation*, vol 3, no 1, pp 17–39, 2015

- Normative requirements for noise measurements are specified in ISO3095:2013[36].
- Normative requirements for vibration measurements should be specified.
- Vibration and noise levels per train type. For example, the pass-by noise level for a train type with smooth wheels is very sensitive to the quality of the rail surface. The smoother the rail surface, the lower the noise level.
- Vibration and noise levels per track section. Noise level in combination with frequency content may be used to evaluate rail surface quality at single spots and/or after rail surface maintenance (e.g. grinding).
- Position of noise emission points – mainly in the vertical direction and along the line As an example of the influence of the vertical position, noise emission from a wheel is easier to shield off than noise emitted from the catenary. As an example of the importance of the position along the lines, impact noise at crossing transitions can be considered.

7.6.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

- Noise levels per train type – Every track situation has its individual dynamic and acoustic fingerprint. Thresholds based on maintenance status of the vehicles allows for monitoring of time dependent changes of noise levels per individual train type. A train with a smooth wheel surface will generate a narrow sound distribution. Variation of the 50 % quartile is then a good indicator of changes in rail surface quality. Additional observation of train velocity compensated frequency distributions can be used to indicate which irregularity wavelengths that are predominant on the rail surface.
- Noise level - Comparison of individual trains at different track situations (e.g. switch and open track) allows a monitoring of maintenance status of individual assets. Smooth wheels will show a larger influence on poorly maintained impact sources (e.g. switch, joints, *etc*).

Short track defects, dipped rails at welded and insulated rail joints can be found from track geometry recording cars. To capture the essential track geometry characteristics, RIVAS proposed to introduce a new wavelength band containing wavelengths in the interval 0.5 – 3 m for the assessment of track geometry measurements. Out-of-round wheels can be identified from wheel load detectors.

7.6.3.1 EXAMPLE OF AN OPERATIONAL MONITORING SYSTEM

As an example of how noise monitoring can be used in operations, we take the work of DB related to its target to reduce the railway induced sound level by 10 dB(A) until 2020. This is to be achieved by

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[36] ISO 3095:2013, Railway applications – acoustics – measurements of noise emitted by railbound vehicles

mitigation measures applied in the infrastructure and the surroundings (e.g. sound barrier, rail damper, noise insulation windows, *etc*). One main focus is to achieve a decrease of rolling noise levels by retrofitting of cast iron to composite brake blocks on freight rolling stock. DB infrastructure decided to install monitoring stations in order to show the status and time dependency of sound level at densely trafficked freight corridors. Three different types of measurement devices have been designed with different levels of complexity:

1. Basic device
2. Mobile device
3. Combination device

In the basic device only sound pressure data of passing trains is collected. The mobile device measures also axle loads and sound pressure levels of passing vehicles, and allows for precise vehicle identification. The combination device combines measurements of different track vibrations and a detection of out of round wheels based on the acoustic entities, see Figure 11. The combination of acoustic data and additional physical parameters allows for a deeper investigation of effects and the assessment of the influencing relevance of each parameter.

Results from two stations are published weekly for public interest. The aim is to show a decrease of rolling noise levels achieved by the retrofitting of cast iron to composite brake blocks of freight rolling stock. An example of result is shown in Figure 12.

Detailed analysis of wheel-rail contact forces allows also to assess the proportion of retrofitted wagons (change from cast iron to composite brake blocks), see Figure 13.

The reproducibility between different monitoring stations and test sites regarding measured noise measurements was investigated by field measurements and numerical simulations in the UIC project HRMS. Based on data from a monitoring system installed at Deutsch-Wagram in Austria, the influence of weather conditions (temperature, rain and snow) on pass-by noise levels and rail bration was assessed. It was concluded that the track superstructure design used at Deutsch-Wagram (60 kg/m rails, rail pads with dynamic stiffness in the order of 700 – 1000 kN/mm, and mono-block concrete sleepers on ballast) is appropriate for noise monitoring since the variation of measured noise levels for the studied range of weather conditions has a standard deviation of less than 2 dB. For such a track design, it is not essential to apply a correction procedure to account for seasonal variations (except in the case of snow). Further, based on a numerical parameter study, it was found that for ground surfaces with low sound reflection, the influence of ground surface level (when varying from 0.2 to 2 m) on predicted pass-by noise level is in the order of 1 dB. For more details on work performed in HRMS, see[37, 38].

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[37] J C O Nielsen, E Augis and F Biebl: Reproducibility of railway noise measurements – influence of test site conditions, *Proceedings of the 12th International Workshop on Railway Noise*, Terrigal, Australia, 2016

Basic device	
Mobile Device	
Combination Device	

Figure 11 Three-stage approach of measurement devices

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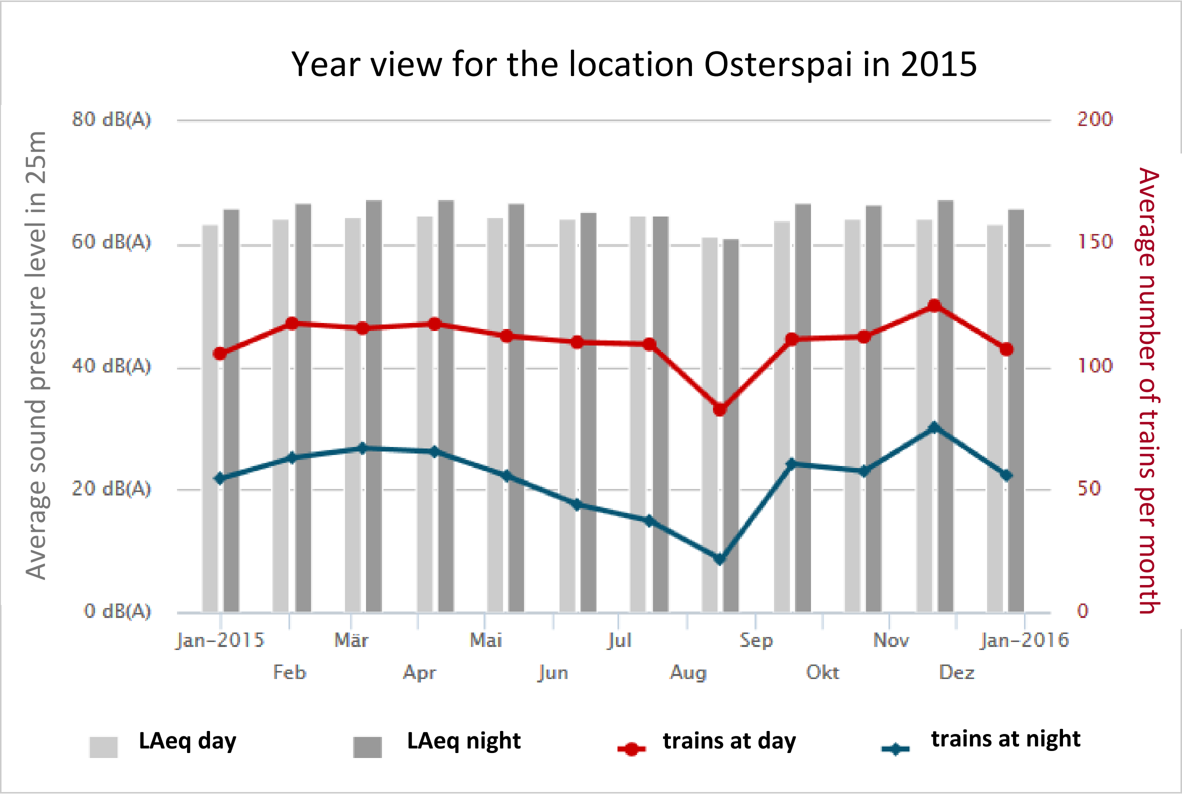
[38] M Asplund, M Palo, S Famurewa and M Rantatalo: A study of railway wheel profile parameters used as indicators of an increased risk of wheel defects, *IMechE Journal of Rail and Rapid Transit*, vol 230, no 2, pp 323-334, 2016



LAeq…sound pressure level

Figure 12 Monthly results in 2015 from the site Osterspai

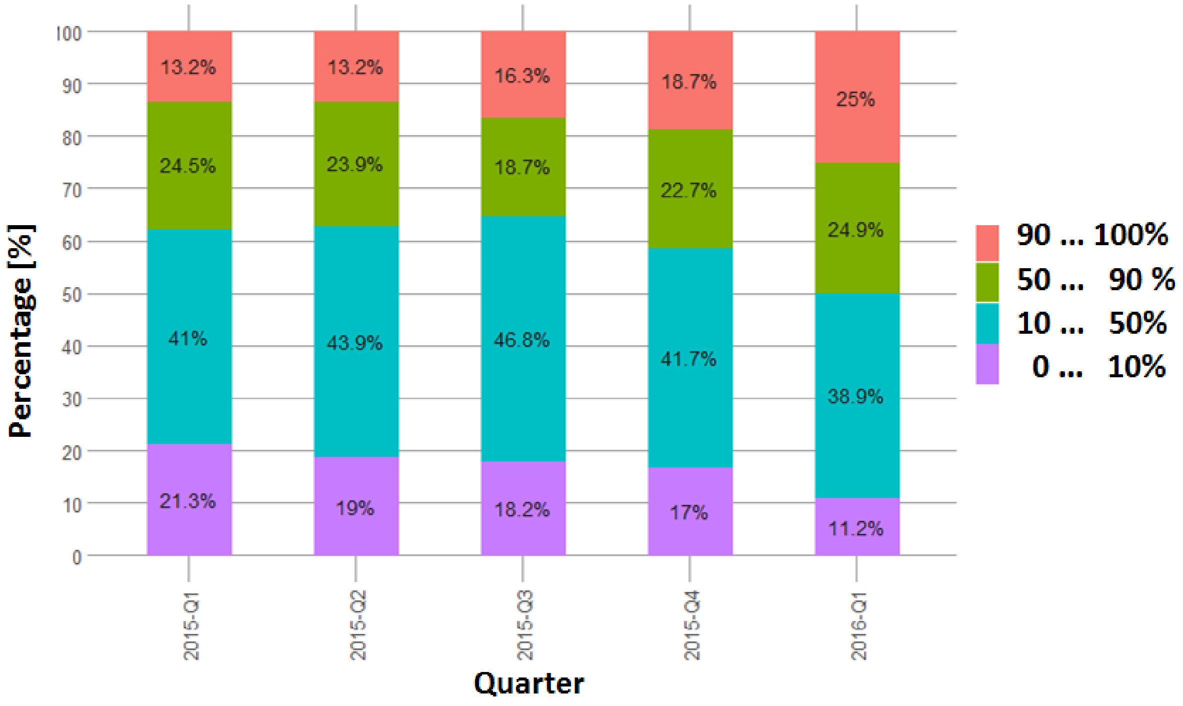


Figure 13 Quarterly proportion of retrofitted wagons per cargo train in Osterspai

7.7 PARTICLE EMISSIONS

7.7.1 KEY PARAMETERS

For an overview of particle emissions in railway operations, see for example the literature survey by Abbasi et al[39]. Key parameters regarding particle emissions include:

Particle concentration – This concerns especially small sized particles – PM_{10} and $PM_{2.5}$ – that are likely to penetrate deep into lungs and thereby cause damage.

Toxicity of the particles – Particles emitted from railways (subway) are mainly iron based and can caused DNA damage. In contrast, particles collected on streets are more potent to induce

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[39] S Abbasi, A Jansson, U Sellgren and U Olofsson: Particle Emissions From Rail Traffic: A Literature Review, *Critical Reviews In Environmental Science and Technology*, vol 43, no 23, 2013

inflammatory cytokines. Particles from tire-road wear (collected using a road simulator) were found to be genotoxic and able to induce cytokines[40].

7.7.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

In general particle emissions are not commonly measured in railway environments. The exception may be during the construction phase where there is a need to assure that emissions are below limit values. Another exception may be in metro lines and similar where the particle concentration is related to the air functioning and an indicator of the efficiency of the air supply system.

7.7.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

Particle concentrations can be directly measured. Complications here are that the concentrations will be highly dependent on the surrounding environment. Even in the relatively confined environment of a tunnel it is not straightforward to get unequivocal measurements[41] since the result may depend on the direction of the train, and be influenced by previous trains. Further, it is difficult to separate particle emissions from the passing train from emissions resulting from particles being swept up from the track and/or off tunnel walls etc.

Another way to measure particle emissions is through vehicle-mounted measurements. Here complications are that results will vary fairly significantly based on where on the vehicle the measuring equipment is placed. This is especially the case since the emission rates seem to be significantly increased when mechanical breaking is employed[42].

Toxicity is more cumbersome to be estimated. Essentially the toxicity can either be deduced from a study of the chemical content and size distribution of the particles. Alternatively it requires medical examination of the response to the particle emission exposure.

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[40] H L Karlsson, A G Ljungman, J Lindbom, L Möller: Comparison of genotoxic and inflammatory effects of particles generated by wood combustion, a road simulator and collected from street and subway, *Toxicology Letters*, vol 165, no 3, pp 203–211, 2006

[41] E Fridell, M Ferm and A Ekberg: Emissions of particulate matters from railways – emission factors and condition monitoring, *Transportation Research Part D: Transport and Environment*, vol 15, no 4, pp 240–245, 2010

[42] E Fridell, A Björk, M Ferm and A Ekberg: On-board measurements of particulate matter emissions from a passenger train, *IMechE Journal of Rail and Rapid Transit*, vol 225, no 1, pp 99–106, 2011

8 MONITORING OF RAILWAY CORRIDOR

8.1 FREE SPACE IN THE LOAD GAUGE

The detection of clearance gauge and the corresponding monitoring are fairly standard assessments that are dealt with using measurement techniques according to the state-of-the-art at European railway networks. This is described in the following section.

8.2 CLEARANCE GAUGE

The clearance gauge is the free space on the track required to ensure special transports and approvals of new rolling stock. An example of the clearance gauge is shown in Figure 14 below.

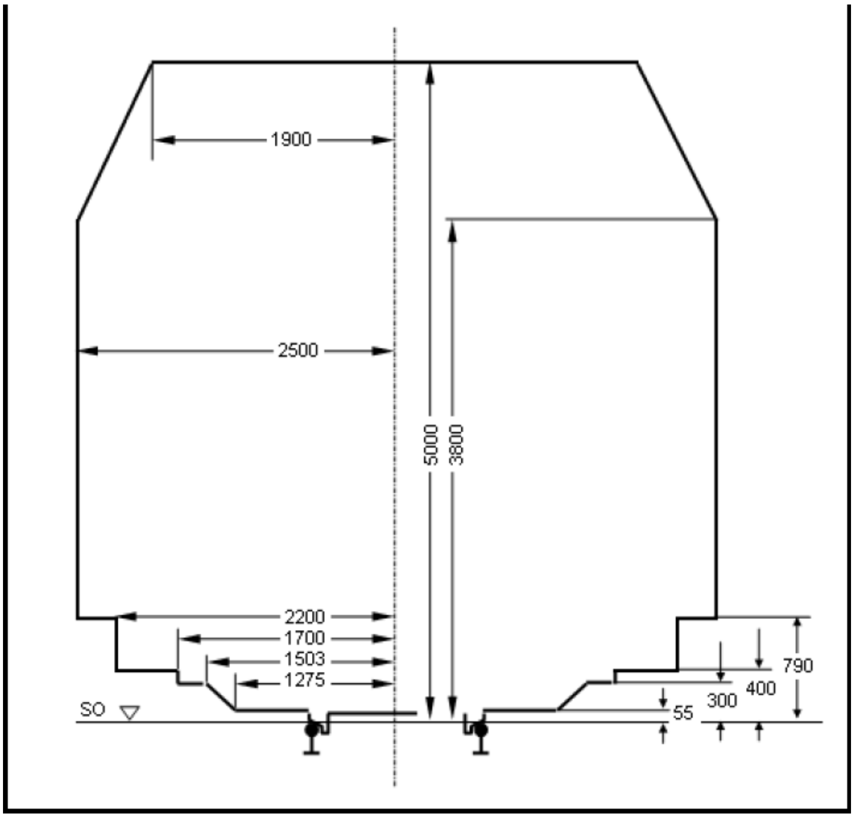
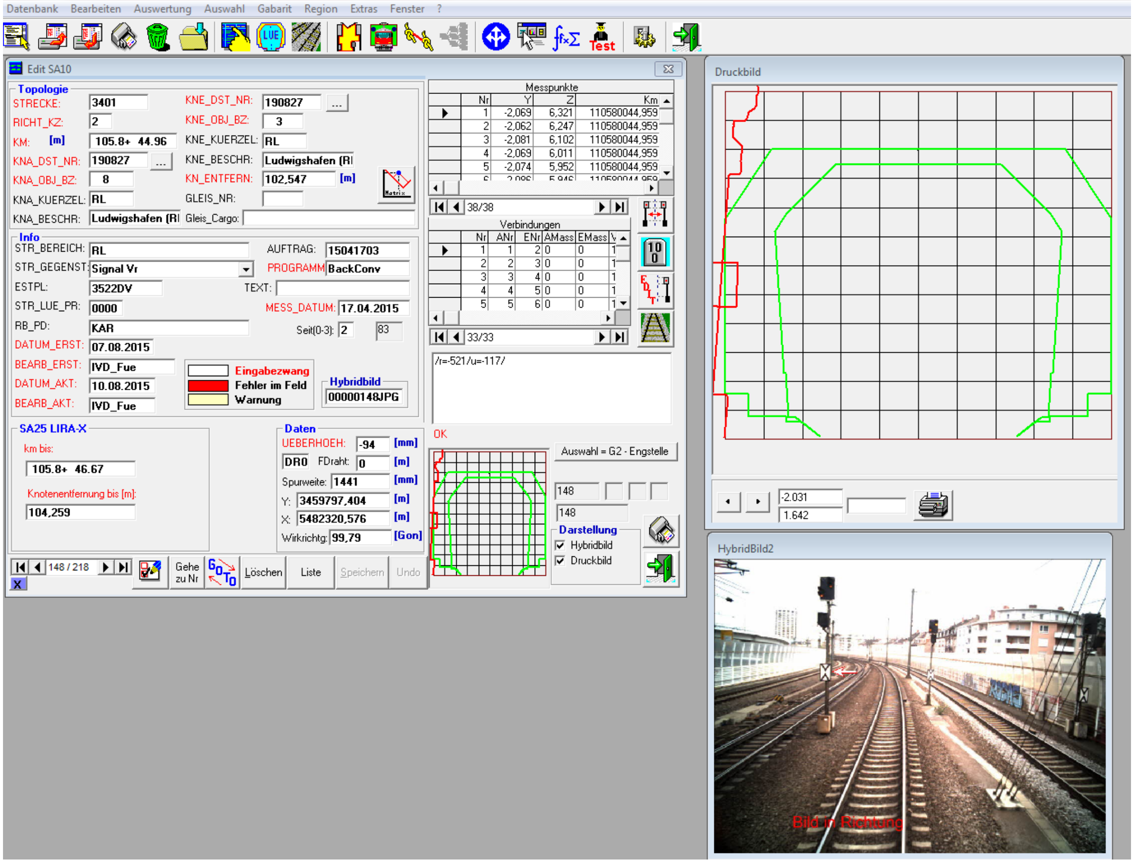


Figure 14 Space for the narrow places/constriction

Within this space all solid objects (station platforms, signals, tunnels, bridges *etc*) are identified (using different measuring systems) and typically documented in a database.

Examples of different measuring systems to acquire position data of the fixed objects are stationary systems that feature photography or employ laser detection. There are also systems that are useful for the detection of localized areas, for instance the mobile system called Limez III. The train Limez III is for the detection of bulk data over complete routes. Measurement speed is up to 100 Km/h.

The measurements need to be documented. A typical way of documenting is in a clearance database. Here the detected and evaluated objects are stored. Typical data on these objects include: route number, direction indicator, kilometre mileage, super-elevation, and image. An example of an information screen is showed in Figure 15.



Topologie
STRECKE: 3401
RICHT_KZ: 2
KM: [m] 105.8+ 44.96
KNA_DST_NR: 190827
KNA_OBJ_BZ: 8
KNA_KUERZEL: RL
KNA_BESCHR: Ludwigshafen (Rl
KNE_DST_NR: 190827
KNE_OBJ_BZ: 3
KNE_KUERZEL: RL
KNE_BESCHR: Ludwigshafen (Rl
KN_ENTFERN: 102,547 [m]
GLEIS_NR:
Gleis_Cargo:

Info
STR_BEREICH: RL
STR_GEGENST: Signal Vr
ESTPL: 3522DV
STR_LUE_PR: 0000
RB_PD: KAR
DATUM_ERST: 07.08.2015
BEARB_ERST: IVD_Fue
DATUM_AKT: 10.08.2015
BEARB_AKT: IVD_Fue
AUFTRAG: 15041703
PROGRAMM BackConv
TEXT:
MESS_DATUM: 17.04.2015
Seit(0-3): 2 83
☐ Eingabezwang
🟥 Fehler im Feld
🟨 Warnung
Hybridbild 00000148JPG

SA25 LIRA-X
km bis: 105.8+ 46.67
Knotenentfernung bis [m]: 104,259

Daten
UEBERHOEH: -94 [mm]
DR0 FDraht: 0 [m]
Spurweite: 1441 [mm]
Y: 3459797,404 [m]
X: 5482320,576 [m]
Wirkrichtg: 99,79 [Gon]

148 / 218

Messpunkte

	Nr	Y	Z	Km
▶	1	-2,069	6,321	110580044,959
	2	-2,062	6,247	110580044,959
	3	-2,081	6,102	110580044,959
	4	-2,069	6,011	110580044,959
	5	-2,074	5,952	110580044,959

38/38

Verbindungen

	Nr	ANr	ENr	AMass	EMass	V
▶	1	1	2	0	0	1
	2	2	3	0	0	1
	3	3	4	0	0	1
	4	4	5	0	0	1
	5	5	6	0	0	1

33/33

/r=-521/u=-117/

OK

Auswahl = G2 - Engstelle

148
148

Darstellung
☑ Hybridbild
☑ Druckbild

-2.031
1.642

Figure 15 Information screen featuring data on a detected obstructing construction

8.3 TRESPASSING AND ANIMALS IN TRACK

Trespassers and (larger) animals in track may cause significant operational delays. Naturally the main objective must be to avoid trespassers and animals in track through different forms of barriers. However, if trespassers or larger animals are present, a functioning detection may avoid accidents and/or unnecessary delays. Note however that false alarms, especially regarding trespassers, may in themselves cause significant operational disturbances since it has to be ensured that the alarm is indeed false.

In summary, some of the most important demands on a monitoring/detection system related to trespassing and animals in track:

- should be able to identify trespassers and (larger) animals in track,
- should be able to distinguish between animals and persons (in order to allow for an appropriate action),
- must keep false alarms at an extremely low level,
- must be robust in terms of providing the same detection level despite environmental conditions such as weather (including snow, rain, snowfall *etc*) and light (day, night).

9 MONITORING OF TRACK

This chapter deals with key parameters of the track system. This includes also the track construction of switches and crossings. For each set of parameters, the presentation outlines the nature of the key variables, suitable status indicators, how these relate to modelling/prediction of track status, and how/if measurable data can be translated into the identified key parameters.

9.1 OVERALL CONDITION – TRACK GEOMETRY AND STIFFNESS

TRACK GEOMETRY

Perhaps the most commonly measured track parameter is the track geometry. Measurement procedures are to a large extent standardised, and there exist a vast amount of commercially available measurement equipment. For this reason, the topic will not be extensively covered in this report.

One should note that track geometry has an influence on the overall track deterioration[43, 44] in terms of track shift, wear and rolling contact fatigue. This mainly relates to the local track geometry and is also influenced by parameters such as wheel and rail profiles. Further, the track geometry will have an effect on passenger comfort. In this respect, it is mainly the overall track geometry that is influential. Finally, the track geometry will have an effect on safety, especially related to flange climbing[45]. Here the influence mainly relates to point-like track geometry defects or geometrical defects with very limited extension. Investigations in the D-RAIL project[46] showed that track geometry measurements are one of the most efficient methods of preventing derailments of freight trains. In detail, it was shown that more than half of all derailments (and a share of 75 % of the costs) are addressed by only three types of interventions: hot axle box and hot wheel detectors, axle load checkpoints and track geometry measurement systems.

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[43] K Karttunen, E Kabo and A Ekberg: The influence of track geometry irregularities on rolling contact fatigue, *Wear*, vol 314, nos 1-2, pp 78–86, 2014

[44] K Karttunen, E Kabo, A Ekberg: A numerical study of the influence of lateral geometry irregularities on mechanical deterioration of freight tracks, *IMechE Journal of Rail and Rapid Transit*, vol 226, no 6, pp 575–586, 2012

[45] F Braghin, A Ekberg, B Pålsson, D Sala, D Nicklisch, E Kabo, P Allen, P Shackleton, T Vernersson and M Pineau: D-RAIL Deliverable D3.2: Analysis and mitigation of derailment, assessment and commercial impact, 283 pp + annex 18 pp, 2013

[46] F Defossez, L Hejzlar, M Krueger, W Nawabi, A Ekberg, G Boisseau and M Haltuf: D-RAIL Deliverable D8.4: Exploitation of results from DRAIL, 17 pp, 2014

VERTICAL AND LATERAL STIFFNESS AND RESISTANCE

The vertical stiffness of the track will influence the vertical contact forces between wheel and rail. In particular stiffness variations along the track may cause very high contact load magnitudes. One consequence of this is that stiff track structures are more sensitive to hanging sleepers than softer tracks[47.] In contrast softer tracks generally lead to higher bending moments in the rail[48]. Stiffness variations are also a reason for high load magnitudes (and related damage formations) at transitions to bridges, switches & crossings *etc*.

As elaborated in the INNOTRACK-project, vertical track stiffness may also be an indication of the geotechnical condition of the track, see e.g.[49].

In a higher resolution, the track stiffness variations along a sleeper are crucial in determining the bending moments in the sleeper (or slab), and thereby the risk of sleeper fractures. It may also result in uneven settlements of the sleeper.

For slab track, the corresponding scenario is stiffness variation across (and along) the slab that may lead to cracking of the slab and deteriorated (vertical) track geometry. Such complications are very costly to mitigate.

Lateral track stiffness is an essential parameter for controlling track shift and (in the extreme case) sun kink formation (i.e. lateral buckling of the track). This is especially important in sharp curves where the lateral resistance of the track also need to endure the curving forces.

9.1.1 KEY PARAMETERS

For track geometry, the key parameters can be divided into the nominal geometry and deviations. In simplistic terms, the key parameters are the (relative) positions of the two rails along the track. If this is known, suitable measures for different types of analyses can be derived.

Two complications could be mentioned here. The first is that the track geometry is (to a smaller or larger degree) influenced by the loading of the track. If this is a significant effect (as for example is the case with poor fastenings), it has to be considered. This typically is made through measurements of a loaded track using a measurement vehicle. The second complication is that wear of the rail profiles may affect the track geometry depending on the nature of the wear and how the measurements are carried out and analysed.

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[47] A Ekberg, E Kabo and J C O Nielsen: Allowable wheel loads, crack sizes and inspection intervals to prevent rail breaks, Proceedings of the 11th International Heavy Haul Association Conference (IHHA 2015), Perth, Australia, pp 30–38, 2015

[48] *ibidem*

[49] Chapter 4 of A Ekberg and B Paulsson (eds): INNOTRACK–Concluding technical report, International Union of Railways (UIC), ISBN 978-2-7461-1850-8, 288 pp, 2010 and references therein

As for vertical track stiffness, the simplistic aim is to obtain the stiffness of the track support along and across the track. Here complications are the frequency- and pre-load dependence of the stiffness. Further, it is generally difficult to distinguish the contribution from different parts of the track structure (rail, sleeper, ballast, sub-ballast *etc*).

9.1.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

For track geometry there are a number of standardized status indictors both on a local level (e.g. rail gauge, track twist, deviation of a local track geometry fault) and as aggregated values (e.g. different track quality measures essentially based on the statistical distribution of track faults).

In general terms, absolute magnitudes of vertical stiffness as well as variations along and across the track are needed to assess the current status. These measures can then be translated to various quality measures depending on the aim of the evaluation.

Regarding lateral stiffness, the absolute magnitude is of importance. Here local variations are likely to have less of an influence even though variations between sleepers will have an effect. In addition, the lateral stiffness needs to be put in context with the track geometry in the sense that a higher lateral stiffness is generally of more importance in curves.

Finally one can say that for vertical stiffness there is an ideal range where the stiffness is high enough to ensure proper support, but low enough not to induce to severe effects of overloads, nor be too sensitive to stiffness (and geometry) variations. The limits of this “optimum range” vary depending on operational and maintenance conditions. In contrast, for lateral stiffness a higher stiffness is basically always better (however typically more expensive to maintain).

9.1.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

TRACK GEOMETRY

As mentioned, track geometry can be determined by different methods and measurement arrangements. They always consist of a sensor system for scanning the track and typically inertial measurement techniques to determine the different values of the track geometry.

If multiple touch points on the rail exist, this allows for an angular-based method or a sliding chord to determine of the horizontal and vertical alignment. In such a case expenses for the inertial measuring unit inside the geometry measurement system can be reduced and a possibly a related minimum speed of the system can be avoided.

In such systems, in general, a frequency response of the measuring system within target values must be considered for shape-persistence. If the track-geometry measurement vehicles are operating at high speed, non-contact probing is necessary at least partly. There are possibilities of employing e.g. laser measurements to achieve this.

As an example of operational practices, it can be noticed that DB operates different systems

- 140 km/h up to 320 km/h,
- scan distances from 0,16 m up to 0,32 m,
- optical and inertial sensoring,
- cross-section-based and angular-based systems,
- accuracy about 0.3 mm over all values.

TRACK STIFFNESS

Typically, measurements of track stiffness (e.g. stationary or from moving vehicles) will provide (frequency dependent) stiffness magnitudes. In general, these cannot distinguish between the influences of the different components in the track (rail, rail pad, sleeper, ballast, substructure *etc*). In order to obtain such information, the different components need to be tested separately and/or the measurements be supported by additional analyses (e.g. of the bending stiffness of the rail – to give a simple case).

A resolution of the stiffness high enough to e.g. characterise the stiffness variations under a sleeper is typically not feasible to obtain with traditional measurement techniques. Instead measurements of lower resolution need to be supported by additional knowledge, simulations and observations to obtain estimations of such kinds of data. Research in this area is in progress.

From the measured data, suitable measures of stiffness magnitudes and variations can be derived. Depending on the aim of the analysis, different measures may be useful. Some examples are:

- To evaluate wheel–rail contact forces and the risk of settlements, the distribution of stiffness variations along the track is a suitable measure to be combined with numerical analyses of train–track interaction.
- For investigations of the risk of lateral buckling, the lateral stiffness variation along the track is suitable. Here an extreme value analysis (typically of a moving average over some meters), and a cross-correlation analysis towards track curvature are useful approaches.
- To establish the risk of rail breaks, the amount of hanging sleepers (or short sections with very low vertical support) are of interest.
- To establish suitable loads for sleeper design, the vertical stiffness variation along the sleeper is a very important parameter.

- To assess the risk of ground-borne vibrations, the frequency variation in track stiffness may be of interest.

9.2 CRACKS IN RAILS

9.2.1 KEY PARAMETERS

The most important parameters are

- crack depth (most importantly, the maximum depth that any crack reaches)
- crack density and extension of cracked zone
- crack characteristics (e.g. following UIC Leaflet 712) in order to establish root cause(s)

These parameters are needed in order to plan a suitable mitigation strategy (typically grinding) that removes all cracks well in time before they become dangerous.

If also the root cause is to be evaluated, more detailed crack characteristics need to be evaluated. In addition, more information (on operating vehicles, track conditions *etc*) would then also be needed, see other relevant sections in Chapter 7 and in this chapter.

9.2.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

Suitable status indicators should indicate the amount of cracking (e.g. the percentage of affected track), and the severity (e.g. some percentile of the crack depth). To further understand causes *etc*, suitable indicators may be in which curve radius range cracks occur, characteristics of cracks *etc*.

Such status indicators can then be coupled to numerical simulations to estimate remaining crack growth life until fracture. This can be done either in a deterministic or a statistical analysis.

9.2.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

Techniques to translate measured data (using e.g. eddy current or ultrasonic measurements) into key parameters currently exist. There are however limitations e.g. in assessing both the depth and the length of a crack. Details on these limitations depend on the measurement technique.

More advanced methods to fully characterise the cracks are currently being researched. Currently such methods are generally too expensive and time consuming to be operationally viable. When (and if) they are operationally feasible, a main challenge will be to translate the massive amount of data such analyses could provide into manageable key parameters.

9.2.3.1 EXAMPLE OF OPERATIONAL MONITORING SYSTEMS

ULTRASONIC TESTING

As a first example of current monitoring system, we take the ultrasonic testing carried out with the DB Inspection Train. The aim of this monitoring is to guarantee safety. The rails are inspected periodically and defects are detected and assessed according to the current regulations.

The ultrasonic test system receives data at speeds of up to 60 km/h at a resolution of 3 mm with 16 probes. The equipment of ultrasonic testing technology is using vertical and angle transducers. Testing angles are 70°, 55°, 35°, 0° straight beam probe, 0° dual element transducer. The pulse repetition frequency is maximum 20 kHz. The ultrasound tester consists of four identical 2 test head mounts. Gates are employed for the signal analyses. The data collected during the test run will be represented in a post process.

The test system is designed for the testing of rail profiles according to DIN EN 13674-1. Identification of rail cracks follows European norms, especially Shelling, Belgrospi, Squat.

EDDY CURRENT TESTING

The eddy current testing system at DB is used for the detection of head checks on the rails running edge of threaded rails. The eddy current test system running a test speed of maximum 80 km/h, it carries eight probes at a resolution of 1 mm along the edge of the track driving. The eddy current inspection system works with a mechanically tracking of the probes with a distance of constant 1 mm from the track.

The examination of a rail uses four eddy current probes in an arrangement of angle of 45°, 21°, 11°, and 7°. With the probes, it is damage at depths in the range of approximately 0.1 to 2.7 mm are reliably found and can be evaluated. The mechanical precise tracking of the probes allow these to be positioned at a constant distance of 1 mm from the rail. However at gaps the testing mechanism is temporarily raised.

The data recorded during the testing is evaluated by an expert system in a post-process and determines cracks of the damage category regarding head checks. Automatic evaluation of test data is done in the background by evaluation software. The evaluation is carried out in parallel to, or after the test.

The eddy current testing is the basis of evaluating the existing damage depth or rather the required depth of re-profiling.

9.3 BROKEN SLEEPERS

The discussion below s focused on concrete sleepers. The problem is also very real for timber sleepers, but here the deterioration is typically higher (and thus more visible) for timber sleepers at the time when the sleeper is replaced. Further, the connection of the fastenings in timber sleepers is typically a critical feature.

9.3.1 KEY PARAMETERS

From an operational point of view, the required knowledge for each sleeper is what the current flexibility and strength of the sleeper is. This includes the number of sleepers affected by deterioration. From a maintenance point of view, also the rate of deterioration of these measures is of high importance.

9.3.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

In relation to the key parameters, suitable status indicators are

- identification of cracked sleepers;
- characteristics of cracking (mainly depth, position).

Currently this is mainly carried out by visual inspections. Research is on-going in introducing e.g. digital vision and dynamic measurement techniques.

9.3.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

The described indicators can then be post-processed (with various presumptions required) to e.g. evaluate fraction of sleepers that are damaged, which can be used in correlation analyses towards e.g. track curvature. Such an analysis is fairly straight-forward and can be used for maintenance purposes.

A more sophisticated analysis is e.g. an evaluation of the residual load carrying capacity. This requires additional simulations and can be of use in evaluating and quantifying the degradation over time in order to establish maintenance strategies and improve track structure design.

9.4 LOOSE FASTENINGS AND WORN DOWN RAIL PADS

9.4.1 KEY PARAMETERS

The main parameter is if the fastening / rail pad exists. More detailed information would be if the fastening provides a proper force/stiffness and the state of the rail pad.

9.4.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

Basically the parameters of operational influence are which fastenings / rail pads that are malfunctioning / missing and the position of these. This knowledge can then be translated to maintenance strategies and also used to predict e.g. altered dynamic characteristics, increased risk of lateral buckling *etc*.

9.4.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

Current procedures range from visual inspection during standard maintenance to camera monitoring. Regardless, the translation from measurements to key parameters is trivial. The major complication is instead to obtain a sufficiently exact, robust and cost-efficient inspection/evaluation method.

9.5 CONDITION MONITORING FOR SWITCHES AND CROSSINGS – ADDITIONAL PARAMETERS

Condition monitoring will besides the methods available for track will also cover the certain components in the Switches and Crossings (S&C) that differ from normal track.

The biggest differences are the movable parts the different design of rails and fastening systems. All condition monitoring applicable for plain track should therefore be considered (and in some cases be adapted) to the constraints that the S&C gives. Therefor this section described the technology used and technology that that should be developed or more adopted than the situation is given today.

Condition monitoring can be carried out both on site and by movable units. There are certain benefits for both ways of gathering the data. On site equipment will have a capability of continuous monitoring, on the other hand movable equipment can be used to check the status on many different S&Cs.

The information needed that can be covered by monitoring has been described in In2Rail deliverable D2.3 “Embedded & integrated sensor: Systems design hierarchy report” and is just summarized here in Table 9.1 and Table 9.2. Within In2Rail the works concentrates on monitoring that can be done by equipment permanently mounted on site. Therefor the discussion in this section is more about equipment that can be moved.

Table 9.1 Information needed for switches and crossings. See In2Rail, Deliverable D2.3 for details.

Information needed	**Suitable mounting**
Structural displacement and impact force in crossing panel. (Impact force doesn’t follow directly from the acceleration, but can be estimated.)	Embedded
• Crossing deformation • Switch rail deformation • Contact zone This information can be used to estimate contact loads and the fatigue life of the crossing and switch rail. It might also be possible to estimate where a particular wheel makes the transition.	Partly embedded, but mainly vehicle
• Switch panel geometry • Crossing running surface geometry Repeated profile measurement will give a better understanding of wear and deformations.	Vehicle
Check rail gauge.	Vehicle
Load distribution and transfer from rails to sleepers.	Embedded and through simulation
Structural deformation. With information on sleeper deformations and accelerations it should be possible to obtain information about how the impact load of the crossing propagates down through the track structure.	Embedded
Information on the sleeper–ballast contact pressure This is the most important parameter when it comes to determining ballast crushing and track settlement.	Embedded
Local crossing damage (e.g. RCF, squats, cracks *etc*); Type and location of damage for the validation of damage models.	Vehicle with follow up through manual measurements
Long term development of track irregularities/settlements	Embedded, but permanent long term deformation should be possible to measure by vehicle
Longitudinal stresses	Embedded and vehicle
Sleeper condition, remaining useful life	Embedded and vehicle

Friction or poorly adjusted position detectors	Embedded
Switch blade form during movement and final position	Embedded
Switch blade obstruction	Embedded
Motor, control and stress bar condition	Embedded
Local weather prognosis	Embedded and information from other sources

Table 9.2 Key information and possibility to measure by condition monitoring with embedded sensors. See In2Rail, Deliverable D2.3 for details.

Information sought/purpose	**Quantity to be measured**	**Measurement technology**	**Data used for**
Structural displacement and impact force in crossing panel. The impact force doesn't follow directly from the acceleration, but can be estimated.	- Vertical displacement and acceleration - Noise	- Accelerometer - Displacement sensors - Microphone	- Management - Maintenance - Research & Development
- Crossing deformation - Switch rail deformation - Contact zone This information can be used to estimate contact loads and the fatigue life of the crossing and switch rail. It might also be possible to estimate where a particular wheel makes the transition.	- Strain - Contact area - Lateral wheel position at transition - Forces in checkrail	- Strain gauge - Ultrasonic probe - Radar, lidar - Piezo-electrical sensors	- Research & Development
- Switch panel geometry - Crossing running surface geometry Repeated profile measurement will give a better understanding of wear and deformations.	- Rail profile - Kink of crossing	- 3D-laser-scanner	- Maintenance - Research & Development
Check rail gauge	Distance	Laser	Maintenance
How the load is distributed and transferred from rails to sleepers.	Forces in rail-sleeper connections	Piezo-electrical load cells	Research & Development
Structural deformation. With information on sleeper deformations and accelerations it should be possible to obtain information	- Sleeper displacements and accelerations along	- Accelerometer - Displacement sensors	Research & Development

Information sought/purpose	Quantity to be measured	Measurement technology	Data used for
about how the impact load of the crossing propagates down through the track structure.	their length - Ballast displacement		
Information on the sleeper-ballast contact pressure is the most important parameter when it comes to determining ballast crushing and track settlement.	Sleeper-ballast contact pressure	Pressure sensors	Research & Development
- Local crossing damage (e.g. RCF, squats, cracks *etc*); - Type and location of damage for the validation of damage models.	Cracks	Ultrasonic probe (using long wave), eddy current and acoustic emission	- Maintenance - Research & Development
Long term development of track irregularities/settlements	- Track geometry (vehicle based) - 3D laser scanner on site	Track geometry car/In service vehicle with accelerometers	Maintenance Research & Development
Longitudinal stresses	- Strain - Rail temperature	- Strain gauge - Temperature sensor	Operation
Sleeper condition, remaining useful life	Sleeper strength	Acoustic emission	- Management - Maintenance
Friction or poorly adjusted position detectors	Energy consumption over time for the movement	Electric current, force, position, time of movement	- Operation - Maintenance - Management
Switch blade form during movement and final position	Form of the switch blade	- Fibre-optic probes - Strain - Machine vision - 3D scanner	Research & Development
Switch blade obstruction	Picture to identify objects	Machine vision	Operation
Motor, control and stress bar condition	Vibration in different type of bars	Accelerometers	- Operation - Maintenance - Management
Local weather prognosis	- Outdoor temperature - Rail temperature - Wind	- Temperature sensor - Anemometer - Hygroscope	Operation

Information sought/purpose	Quantity to be measured	Measurement technology	Data used for
	- Moisture - Precipitation		

The following subsections discuss available and future methods to capture data by moveable equipment.

9.5.1 MOVABLE EQUIPMENT

Measurement systems have been developed for dedicated trains such as track geometry cars, Non Destructive Testing cars, in service trains, trolleys and hand held units. A more futuristic idea is to use automated drones to perform some of the measurements. The measurement systems used can broadly be described in the fields

- Physical properties, such as force, acceleration, rotation, distance, wave propagation *etc*
- Chemical properties, for instance particle and gas emissions
- Electrical measurement system
- Noise measurement systems
- Vision and scanner systems

The speed of the vehicle is one important factor when designing the system but most of the possible measurement systems can be used by relatively high speed (that is above 250 km/h). Some system do not exist on high-speed trains such as ultrasonic and eddy current measurement system. Trolleys and hand held equipment is not suitable for measuring acceleration and cannot measure level and alignment. On the other hand for instance ultrasonic and eddy current is measured by hand held equipment to verify failures detected by trains.

9.5.2 KEY PARAMETERS

The following parameters could be used for defining current status by condition monitoring of S&C:

- Switchblade profile wear
- Crossing profile wear
- Track geometry
- Electrical current measurement of switch blade movement
- Number of indicated rail defects by using NDT-technologies

9.5.3 MEASURE DEFORMATION AND RAIL PROFILE

9.5.3.1 MEASURING DEFORMATION AND RAIL PROFILE AT SPEEDS OVER 40 KM/H

The rail deformation is different in the transition zones than the deformation for normal rail and should therefore be measured. A possible measurement technology by vehicle that is in use in for instance the Netherlands is to measure by laser rail profile. This is already done at 40 km/h and is possible at 80 km/h with trains dedicated for S&C measurement. Even higher speed is required to integrate the measurement with ordinary measurement trains. This is of course possible because the normal rail profile is today measured at 250 km/h or higher. The difference is that an S&C needs to be measured with 10-25 mm spacing at high speed, which is not done today.

Similar to measurements of rail profile is to use this technology to scan the surface to detect defects. This needs to be done at spacing of perhaps 2 mm. The available technology for laser scanning can take 5000 samples per seconds. So at 90 km/h it would result in 5 mm spacing. Laser scanning technology to find defects compare the scanned pattern with previously stored patterns. The amount of data to be stored to compare all crossings in the railway net is very large and will be one of the challenges. The technology is however currently developed to find missing clips and defects in ordinary rails.

Check rail position and switchblade clearance could also be measured in this way.

Vision systems are used to take images and can be programmed to find visible defects. It has so far not proven to be realistic to automate this for S&C transition areas.

NDT technology needs the full rail profile when measured by train and therefore some parts of the S&C needs to be measured by hand held equipment. Manganese crossings cannot be evaluated by ultrasonics in a reliable way and the SAFT-inspect project has worked on how to improve this. Higher inspection speeds than 40 km/h are also an aim.

9.5.3.2 MEASURING DEFORMATION AND RAIL PROFILE AT LOW SPEED OR MANUALLY

Trolleys for laser scanning rail profiles are already on the market. How well adopted they are for S&C has not yet been explored in Capacity4Rail. In the demonstrators, two new technologies investigated: Hand held 3D scanners that are able to scan with a 2D resolution of 0.5 mm, and a special built scanner for the crossing area. Both of these techniques have the possibility to provide scans within minutes.

9.5.4 MEASURING TRACK IRREGULARITIES/SETTLEMENTS

Track geometry cars already measure track irregularities. These are however still not evaluated for S&C in an advanced way. As a demonstrator Turkish state railways and Trafikverket will show how

S&C automatically can be evaluated from a track-recording car. Absolute or semi-absolute measurements are discussed to speed up the process of absolute positioning tamping. When this is realized, the track-recording car would also be able to measure settlements.

9.5.5 ELECTRICAL CURRENT MEASUREMENT OF SWITCH BLADE MOVEMENT

To measure the electrical current during switchblade movement is an established method to find mechanical and other potential failures in time. These types of measurement can also include measurement of switchblade position during movement and force necessary to move and lock the switchblade[50].

Work is still on-going to improve algorithms to distinguish between different failures modes and also to minimize the number of false alarms. Work in this subject will be performed in In2Rail WP6.

9.5.6 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

There is not any work known where suitable thresholds has been established for all parameters mentioned in the section about S&C beside the measurement electrical current. The thresholds for the other parameters are however possible to define.

A possible way of summarize the status per S&C is to weigh the importance of the actually S&C depending on the effect a failure would have as impact on the traffic.

9.6 RAIL PROFILES

The rail profile measurement detects wear and irregularities of the rail surface arrangements. Hereby periodic errors in wavelengths between 10 mm to 1000 mm are relevant in the longitudinal direction. In the transversal direction, deviations from the wear profile (example 60E2) and the rail head wear are of interest. Additionally, the equivalent conicity becomes increasingly important.

With contactless rail probes (light section sensors), these values can be determined at high speeds, using the triangulation method.

The longitudinal profile hereby either follows of multiple light sections across the rails (chord method) or is determined by a special, longitudinally guided line of light. Also a mechanically probing by the wheel and accelerometers is conceivable.

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[50] Section 6.2 of A Ekberg and B Paulsson (eds): INNOTRACK–Concluding technical report, International Union of Railways (UIC), ISBN 978-2-7461-1850-8, 288 pp, 2010 and references therein

Prior extraction the real rail shape from camera images, all kinds of image errors (disturbance from dirt and water) should be analysed or corrected.

Main operational parameters of a typical measurement system are:

- mechanical tracking system up to 200 km/h with a scan-distance of 0,48 cm
- optical probing of the rails
- inner cross-sectional HD-images
- outer cross-sectional images down to rail-foot outside
- longitudinal bar shooting
- accuracies of 5 µm regarding longitudinal profile, and 1 µm regarding cross profile

9.7 SLEEPER SUPPORT

This topic mainly concerns that the sleeper provides sufficient stiffness and has sufficient strength. These topics have been addressed in sections 9.1 and 9.3, respectively.

9.8 BALLAST CONDITION

The influence of ballast on stiffness has been addressed in 9.1. The current section only addresses additional aspects.

9.8.1 KEY PARAMETERS

In addition to provide additional (vertical and lateral) stiffness, the ballast needs to be sufficiently compacted, provide sufficient internal friction, provide sufficient drainage and be frost resistant. The first two aspects are closely linked to the stiffness and will not be discussed further than by noting that the internal friction is related to the shape of the ballast stones and may be supported by various forms of reinforcement. The latter parameters relate to the cleanliness of the ballast.

9.8.2 SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE

Regarding drainage ability and frost resistance, ideally, the status indicator should be the size distribution of particle sizes in the ballast.

9.8.3 HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS

In practice it is generally not feasible to evaluate the particle size distribution in the ballast since this would require investigations that destroy the compaction of the ballast (in addition to being too costly). Instead, typically indirect assessments are made, i.e. ballast cleanliness is assumed to be insufficient if the drainage is defunct and/or ice is formed in the ballast. Naturally this is not satisfactory. Potential ways to improve the situation in the future could be e.g. geophysical investigations (*cf* the work on this topic in INNOTRACK[49]).

10 MONITORING STATUS OF SUPPORT AND STRUCTURES

10.1 BRIDGES

10.1.1 STRUCTURAL SAFETY

KEY PARAMETERS	SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE	HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS
Internal forces (axial, shear and bending moment)	Internal forces should be controlled to assure an adequate safety level. Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of additional parameters that are required if the monitoring data should be useful and mitigating activities efficient. These include: • Material properties, geometry; • Traffic loads (vertical, longitudinal, lateral); • Environmental conditions (temperature, humidity, wind speed and direction);	The internal forces need to be measured indirectly as resultants of stresses (strains) acting on the cross section of the structural elements. Stresses are computed based on adequate stress-strain relationships. Axial forces in stays/hangers can be measured indirectly from vibration measurements.
Structural stress (strain)	Stresses should be controlled to assure an adequate safety level and service life. Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of additional	Strains can be measured directly. Stresses are computed based on adequate stress-strain relationships.

	parameters that are required if the monitor data should be useful and mitigating activities efficient. These include: • Material properties, geometry; • Traffic loads (vertical, longitudinal, lateral); • Environmental conditions (temperature, humidity, wind speed and direction);	
Dynamic factor	Dynamic factors should be controlled to mitigate the risk of resonance or excessive vibration of the bridge. Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of additional parameters that are required if the monitor data should be useful and mitigating activities efficient. These include: • Traffic loads and speed; • Track irregularities; • Vehicle imperfections (wheel flats, out of round wheels, suspension defects *etc*).	The dynamic factor is computed as the ratio between maximum values of the dynamic and static responses.
Structure topography (deck levelling, column verticality)	Structural deformations (deck, columns, foundations, abutments) should be controlled to assure to assure an adequate safety level.	

10.1.2 TRAFFIC SAFETY

KEY PARAMETERS	SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE	HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS
Vertical acceleration of the deck	The maximum peak values of the vertical acceleration of the deck due to traffic actions should be limited to avoid ballast instability and unacceptable reduction in wheel rail contact forces.	The vertical acceleration of the deck can be measured directly. Here it is crucial that the measurements are made at deck locations where maximum acceleration occurs.
Vertical deflection of the deck throughout each span	The vertical deflection of the deck due to vertical traffic actions should be limited to ensure acceptable vertical track radii and generally robust structures.	The vertical deflection of the deck can be measured directly or indirectly using strain and rotation measurements.
Twist of the deck	The twist of the deck due to vertical and lateral traffic actions, measured along the centre line of each track on the approaches to a bridge and across a bridge, should be limited to minimise the risk of train derailment.	The twist of the deck can be computed based on vertical deflection measured along two parallel longitudinal alignments of the deck.
Rotation of the ends of deck	The rotation of the ends of each deck about a transverse axis or the relative total rotation between adjacent deck ends, due to traffic loading (vertical and lateral), wind loading and temperature loading (transverse differential), should be controlled to limit additional rail stresses, limit uplift forces on rail fastening systems and	The rotations of the deck can be measured directly.

	limit angular discontinuity at expansion devices and switch blades.	
Horizontal transverse deflection	The horizontal transverse deflection due to vertical and lateral traffic actions, wind action and temperature action (transverse differential) actions should be limited to ensure acceptable horizontal track radii. The transverse deformation includes the deformation of the bridge deck and the substructure (including piers, piles and foundations).	The horizontal deflection of the deck can be measured directly or indirectly using strain and rotation measurements.
Horizontal rotation of deck	The horizontal rotation of the deck about a vertical axis at its ends due to due to vertical and lateral traffic actions, wind action and temperature action (transverse differential) should be limited to ensure acceptable horizontal track geometry and passenger comfort	The horizontal rotation of the deck can be measured directly.

10.1.3 TRACK-BRIDGE INTERACTION

KEY PARAMETERS	SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE	HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS
Rail stresses	The additional rail stresses (compression and tension) due to the combined response of the structure and track to variables actions should be limited to avoid track buckling or	The additional rail stress can be measured directly from rail strain. Here it is crucial that the measurements are made at sections where

	rail fractures. Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of additional parameters that are required if the monitor data should be useful and mitigating activities efficient. These include: • Traffic loads (vertical, longitudinal, lateral); • Environmental conditions (temperature, humidity, wind speed and direction, solar radiation); • Rail temperature; • Deck temperature (uniform, gradient); • Rail neutral temperature distribution along the deck; • Axial and bending stiffness of the rail; • Longitudinal/lateral stiffness and resistance of the track; • Vertical stiffness of the track; • Track irregularities (longitudinal level, alignment, cross level, twist).	maximum/minimum stresses occur.
Deformation of the structure: relative longitudinal displacement between the end of a deck and the adjacent abutment or between two consecutive decks	The relative longitudinal displacement due to traction and braking forces should be limited e.g. to avoid ballast deconsolidation.	The relative longitudinal displacement can be measured directly by a displacement sensor (contact or non-contact devices).

Deformation of the structure: relative longitudinal displacement of the upper surface of the deck at the end of a deck due to deformation of the deck	The relative longitudinal displacement due to vertical traffic actions should be limited to avoid ballast deconsolidation.	The relative longitudinal displacement can be measured directly by a displacement sensor.
Deformation of the structure: vertical displacement of the upper surface of a deck relative to the adjacent construction (abutment or another deck)	The relative vertical displacement due to variable actions should be limited to avoid ballast deconsolidation.	The relative vertical displacement can be measured directly by a displacement sensor.
Uplift forces on rail supports and fastening systems	For directly fastened rails the uplift forces under vertical traffic loads should be checked against the relevant limit state (including fatigue) performance characteristics of the rail supports and fastening systems.	The uplift forced needs to be measured indirectly e.g. from rail-support relative displacement measurements.

10.1.4 PASSENGER COMFORT

KEY PARAMETERS	SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE	HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS
Vertical acceleration inside the coach	The vertical acceleration inside the coach, during travel on the approach to, passage over and departure from the bridge, should be limited to assure an adequate level of comfort of the passengers. Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of	The vertical acceleration can be measured directly. Here it is crucial that the measurements are made at locations where maximum acceleration occurs.

	additional parameters that are required if the monitor data should be useful and mitigating activities efficient. These include: • Track irregularities • Vehicle imperfections (wheel flats, out of round wheels, suspension defects *etc*).	

10.1.5 STRUCTURAL HEALTH MONITORING

KEY PARAMETERS	SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE	HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS
Modal parameters: Frequencies, mode shapes and modal damping ratios	The basic premise is that damage alters the stiffness, mass or energy dissipation properties of the bridge; they in turn alter the measured structural dynamic response. As a consequence, the experimental response of a damaged structure during a dynamic investigation moves away from the expected one. Examples of damage identification methods that extract features from the modal parameters are modal strain energy, uniform load flexibility shapes and finite element modal updating. Features used to identify damage in bridge structures are most often derived from linear modal properties. Few studies report the development of damage-sensitive features for bridge structures based on nonlinear	Frequencies and mode shapes need to be measured indirectly from vibration signals of a distributed system of sensors (acceleration or strain sensors). Several Operation Modal Analysis (OMA) methods are available that operate in the time or frequency domains. Examples of output-only methods are the Stochastic Subspace Identification (SSI) method, in the time domain, and the Enhanced Frequency Domain Decomposition method (EFDD), in the frequency domain.

	response characteristics. Changes in damage-sensitive features caused by environmental and operational variability are significant and must be accounted for in bridge applications through statistical pattern classifiers. However, the literature shows little application of this technology to bridge damage detection studies. Also, to account for variability in ambient loading conditions and environmental variability, it is imperative that the statistical pattern classifiers and associated data normalisation procedures must be adopted for these structural health monitoring (SHM) applications. Without this technology it will be difficult to determine if changes in the identified features are caused by damage or by varying operational/environmental conditions. Identifying new damage-sensitive features, particularly those that are based on a nonlinear, time-varying response, will be a focus of research efforts for SHM applications in bridges.	

10.1.6 STRUCTURAL DURABILITY

KEY PARAMETERS	SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE	HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS
Concrete durability: steel reinforcement corrosion	Penetration of corrosion front. The reason for depassivation of	Monitoring using reference electrodes: the penetration of corrosion front is monitored by

	concrete is the result of ingress of chloride ion in chloride laden environment and also because of acidification of interstitial pore solution by ingress of CO2 from atmosphere.	comparing the potential between each rod of the ladder with a reference electrode. Monitoring using macro-cell measurements: A galvanic cell is created which consists of an anode and a cathode. Electrical current between the anode and cathode is measured which is proportional to the dissolution of iron at the anode due to corrosion activity. The change in the galvanic current gives the corrosion rate of the anodic steel in the host material. On the propagation period, during which the rebar corrodes until a maximum tolerable level of damage, corrosion rate has been identified as the most relevant parameter. In addition temperature sensors should be always installed since this parameter directly influences the corrosion rate of reinforcement and transport properties of aggressive agents in concrete cover.
Steel durability: corrosion	Steel thickness reduction.	The steel thickness reduction is measured indirectly from a change in electrical resistance.

10.2 TUNNELS

When monitoring a tunnel structure, there is an important distinction to be made between monitoring how the tunnel impacts the surface level and surrounding infrastructure, and monitoring the behaviour of the tunnel itself.

The monitoring program generally incorporates the measurements of various parameters, such as ground movements, movements of existing structures, ground water movements and pressures and traffic induced vibrations.

In addition, structural parameters can be monitored as well, such as the deformations and stresses of the tunnel.

KEY PARAMETERS	SUITABLE STATUS INDICATORS AND HOW STATUS CAN BE PREDICTED FROM THESE	HOW MEASUREABLE DATA CAN BE TRANSLATED TO KEY PARAMETERS
Ground movements: vertical and lateral deformations	Ground movements should be controlled to mitigate the risks of damage in surrounding infrastructure	Ground movements can be measured directly e.g. using the following techniques: • Survey points • Borros points • Probe extensometers • Fixed borehole extensometers, either measured from the surface or during advance of the tunnel • Tell tales or roof monitors • Heave gages • Conventional Inclinometers • In-place inclinometers • Convergence gages
Movements of existing	The differential movements should be controlled to	The movements of existing structures can be measured

structures	mitigate the risks of damage in surrounding structures	directly e.g. using the following instruments: • Deformation monitoring points • Structural monitoring points • Robotic total stations • Tiltmeters • Utility monitoring points • Horizontal inclinometers • Liquid level gages • Tilt sensors on beams • Crack gages
Ground water behaviour		Groundwater movements and pressures can be measured e.g. using the following instruments: • Observation wells • Open standpipe piezometers • Diaphragm piezometers
Traffic induced vibrations	Traffic induced vibrations should be controlled to mitigate the risks of people discomfort, malfunctioning of sensitive equipment and damage to buildings Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of additional parameters that are required if the monitor data	Vibrations can be measured directly using the acceleration or velocity sensors

	should be useful and mitigating activities efficient. These include: • Traffic loads and speed; • Track irregularities; • Vehicle imperfections (wheel flats, out of round wheels, suspension defects *etc*).	
Tunnel deformation	Tunnel deformation should be controlled to assure an adequate safety level during the tunnel service life.	Various techniques for tunnel convergence monitoring can be used or combined, whether installed on the tunnel surface or operated from within the tunnel. Tunnel convergence can be measured using tape extensometers (contact method) or using a total station (non-contact method). Using motorised high precision total stations in combination with automatic target recognition, the tunnel convergence can continuously be measured and results can be transferred to a computer, giving a warning when predefined thresholds are reached. An alternative to cover more points on the tunnel surface is the use of so called tunnel profile scanners' or profilometers, with an achievable accuracy of around 5 mm. High resolution laser scanning is another method which allows covering a larger part of the tunnel structure with a dense point grid, either from a static set-up or from

		a mobile platform. It allows overcoming several restrictions, such as the available time on site and the accessibility, whereas traditional surveying techniques often fail to meet such requirements. Using laser scanning, a large amount of points can be measured in a very short time frame (up to one million points per second) with a detailed accuracy (millimetre-level). The high-resolution point set is available for further processing, allowing the identification of individual tunnel segments and joints and possible changes in position caused by the deformation of the tunnel structure.
Structural stress (strain)	Stresses should be controlled to assure an adequate safety level during the tunnel service life. Regardless of the exact limits, trends *etc*, that are being evaluated there are a number of additional parameters that are required if the monitor data should be useful and mitigating activities efficient. These include: • Earth pressures; • Ground water pressures.	Strains can be measured directly. Stresses are computed based on adequate stress-strain relationships.
Concrete durability: steel reinforcement corrosion	Penetration of corrosion front. The reason for depassivation of	Monitoring using reference electrodes: the penetration of corrosion front is monitored by

	concrete is the result of ingress of chloride ion in chloride laden environment and also because of acidification of interstitial pore solution by ingress of CO2 from atmosphere.	comparing the potential between each rod of the ladder with a reference electrode. Monitoring using macro-cell measurements: A galvanic cell is created which consists of an anode and a cathode. Electrical current between the anode and cathode is measured which is proportional to the dissolution of iron at the anode due to corrosion activity. The change in the galvanic current gives the corrosion rate of the anodic steel in the host material. On the propagation period, during which the rebar corrodes until a maximum tolerable level of damage, corrosion rate has been identified as the most relevant parameter. In addition temperature sensors should be always installed since this parameter directly influences the corrosion rate of reinforcement and transport properties of aggressive agents in concrete cover.
Steel durability: corrosion	Steel thickness reduction.	The steel thickness reduction is measured indirectly from a change in electrical resistance.

11 MONITORING STATUS OF THE SIGNALLING SYSTEM

The mission of signalling systems may be summarised in two tasks:

- To assure safety of train movement with respect to train movement
- To provide information to the driver about the status of track ahead.

To assure safety of train movement along the line, it is enough to make sure that no other train is located ahead the current one (track occupation information). However if a route is to be defined at a station, it is also necessary to make sure that no other allowed train path uses the same switches or tracks included in the route to be set.

To provide information about track status, conventional signalling uses colour-light signals: each aspect of signal has a meaning, depending on the type of signal (i.e. the function of the signal).

The railway signalling and control systems are used to safely direct railway traffic in order to prevent trains from collisions. This aim needs to take into account that the weight of trains and momentum makes it difficult to stop before reaching the impending obstacle.

Many train control systems involve movement authority being passed from those responsible for each section of a rail network to the train cabin-crew.

The main elements of a traditional signalling and control system include:

- Train detection devices
- Track circuits
- Axle counters
- Mass detectors (often used for tram mass transit)
- Safety systems
- Cab signalling
- Interlocking
- Operating rules
- Fixed signals
- Mechanical signals
- Colour light signals
- Route signalling and speed signalling

- Approach release
- Block signalling
- Entering and leaving a manually controlled block
- Permissive and absolute blocks
- Automatic block
- Fixed block
- Moving block
- Centralized traffic control
- Timetable operation
- Timetable and train order

11.1 THE EUROPEAN RAILWAY TRAFFIC MANAGEMENT SYSTEM – EUROPEAN TRAIN CONTROL SYSTEM (ERTMS-ETCS)

The European Railway Traffic Management System/European Train Control System (ERTMS/ETCS) is the European interoperable railway signalling system that combines automatic train protection (ATP) with the possibility of enhanced network capacity.

The ERTMS/ETCS (European Rail Traffic Management System / European Train Control System) is the standard adopted by European Union to guarantee interoperability on the European railway network, i.e. to allow cross-border operation of trains by means of a unified ATC system.

11.1.1 ERTMS-ETCS LEVELS

The ERTMS concept has been developed in 3 different levels of system architecture: Level 1 & level 2 of ERTMS are already implemented and in revenue service in most European countries.

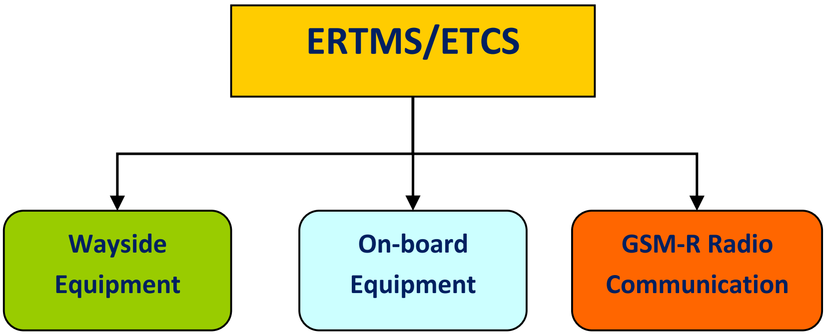


Figure 16 ERTMS/ETCS General System Architecture

Of the three different types of implementation (levels) in Figure 17, Level 1 and Level 2 are based on fixed block operation, while Level 3 uses moving block principle without automatic train operation (ATO) functions (not yet available). The ERTMS/ETCS "levels" define different evolution steps of ERTMS as a train control system, ranging from track to train communications (Level 1) to continuous communications between the train and the radio block centre (Level 2), and moving block technology (Level 3, which is in a conceptual phase), more details are reported below.

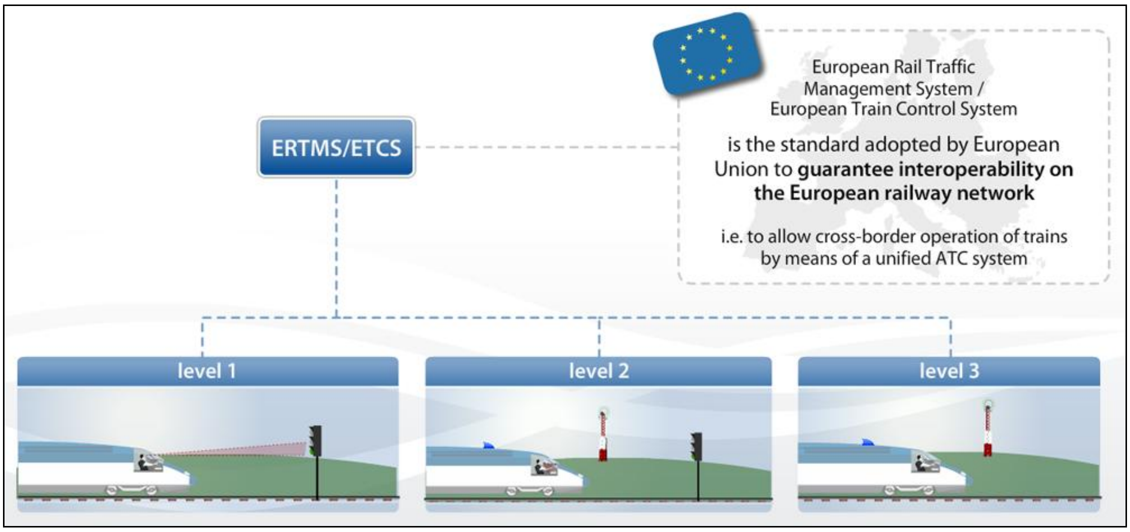


Figure 17 ERTMS/ETCS evolution steps

11.1.1.1 ERTMS-ETCS LEVEL 1

The ERTMS/ETCS Level 1 is based on use of transponders (eurobalise) connected with signals/interlocking to send on-board signalling information. The on-board equipment carries out continuous train supervision according to information received from trackside equipment.

Level 1 operations may overlay existing signalling and thus provide additional safety and improvement in performance with limited impact on train operation.

The ERTMS/ETCS Level 1 can be divided into two main sub-systems; the first (see Figure 18) is composed by eurobalise without infill. Its main functionalities are:

- Overlay to existing signalling & control system
- Movement authorities through eurobalise
- Train integrity & position by track circuit

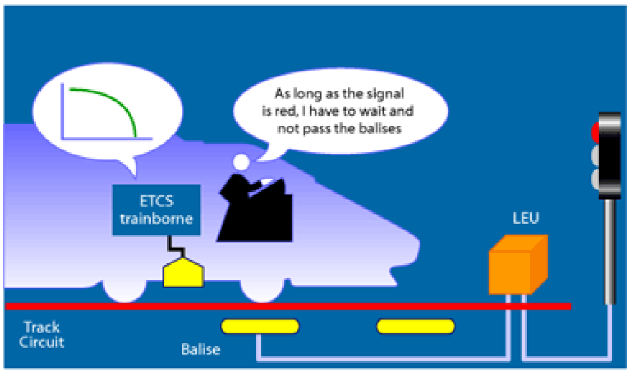


Figure 18 ERTMS/ETCS Level 1 without infill

The second (see Figure 19) is composed by eurobalise with infill (euroloop, radio, or extra balises). The main functionalities are:

- Overlay to existing signalling & control system
- Movement Authorities through eurobalise
- Train integrity & position by track circuit

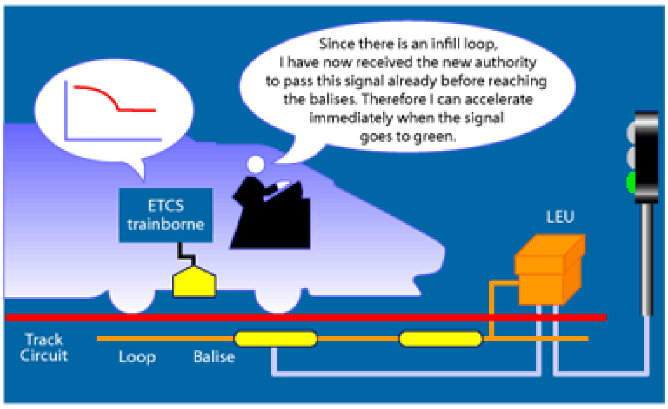


Figure 19 ERTMS/ETCS Level 1 with infill

11.1.1.2 ERTMS-ETCS LEVEL 2

The ERTMS/ETCS Level 2 (see Figure 20) may either overlay existing signalling or be a stand-alone system; in the first case, trains not equipped with on board ERTMS shall be operated according to conventional signalling while equipped trains shall operate in Level 2, in the second case, lineside signals may be replaced by marker boards because train driver has all information needed to operate train on the on board display.

The architecture of Level 2 requires Eurobalises on the track to provide a common space reference to trackside and on board ERTMS; information required to control train movement (distance to target, allowed speed, gradients, *etc*) are sent on board from a central unit called Radio Block Centre (RBC), which collects information from interlocking and calculates space available for movement of each train.

Communication between RBC and on board equipment is supported by GSM-R network, a radio system based on GSM technology with dedicated functions to address railway needs and operated in a specific band

The ERTMS/ETCS Level 2 can be divided into three sub-systems: Eurobalise, Euroradio (GSM-R) and Radio block center (RBC). The main functionalities have been reported below:

- No more trackside signals required
- Movement authorities through GSM-R
- Train position (via eurobalise)

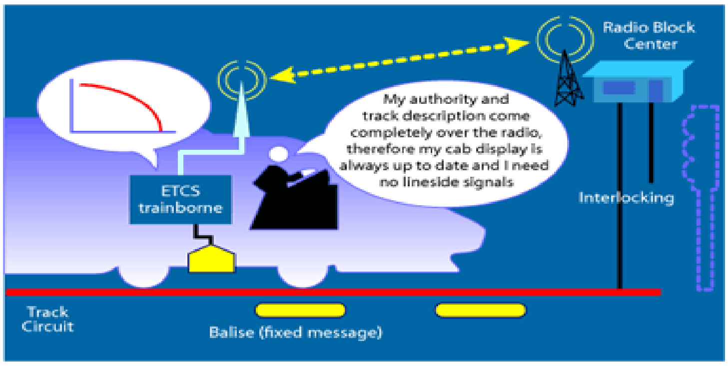


Figure 20 ERTMS/ETCS Level 2

11.1.1.3 ERTMS-ETCS LEVEL 3

The ERTMS/ETCS Level 3 (see Figure 21) implements moving block operation, based on the same architecture of level 2. The main difference between level 2 and level 3 is that no block equipment is available on track in level 3. The radio block centre (RBC) calculates available space for each train on the basis of preceding train rear end position; train integrity supervision (i.e. information that no wagon has been lost) is carried out on board by each train.

The ERTMS/ETCS Level 3 can be divided into three sub-systems: Eurobalise, Euroradio (GSM-R) and Radio Block Center (RBC). The main functionalities have been reported below:

- Movement Authorities through GSM-R
- Authorities through eurobalise

- Train position via eurobalise
- Train integrity on-board
- Moving block

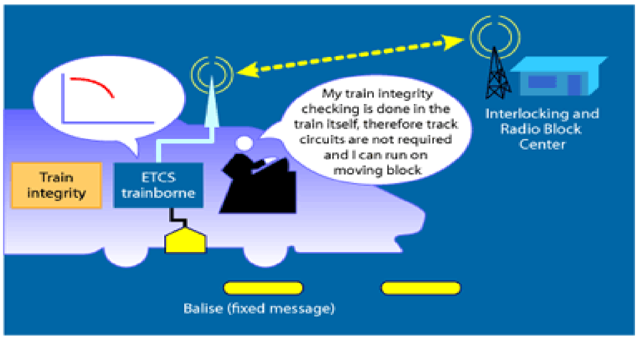


Figure 21 ERTMS/ETCS Level 3

11.1.2 ERTMS/ETCS EQUIPMENT

The ERTMS-ETCS signalling & control equipment (see Figure 22) should be divided into three main sub-systems, which have been described in the following sections.

Below, a general overview of the main elements of the ERTMS/ETCS equipment has been reported: note that different three levels (mentioned above) can be composed by some or all the following items.

11.1.2.1 WAYSIDE EQUIPMENT

The main wayside components have been reported below:

- Lineside Encoder Unit (LEU)
- Eurobalise
- Radio In-Fill Unit (RIU)
- Radio Block Centre
- GSM-R antenna

11.1.2.2 ON-BOARD EQUIPMENT

The main on-board components have been reported below:

- European vital computer (EVC)

- Driver machine interface (DMI)
- Train interface unit (TIU)
- Odometry
- Balise antenna
- GSM-R
- Juridical recorder unit (JRU)

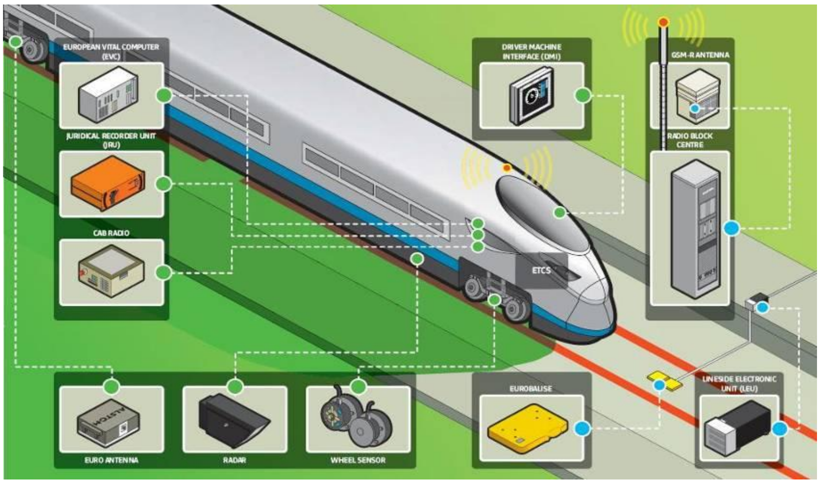


Figure 22 ERTMS/ETCS wayside and on-board equipment

11.1.2.3 RADIO COMMUNICATION SYSTEM

In the context of railway communication and applications, the “Global System for Mobile Communications – Railway” (GSM-R) is the international wireless communications standard. As a sub-system of ERTMS/ETCS, GSM-R technology is used for communications between train and railway regulation control centres: it is based on GSM specifications, defined with “European Integrated Radio Enhanced Network” (EIRENE) and validated with “Mobile Radio for Railways Networks in Europe” (MORANE), which guarantee performance at speeds up to 500 km/h (310 mph), without any communication loss.

11.2 MONITORING SYSTEMS

The overview of the signalling and control systems has allowed the classification of the main components that play a key role in the functional status of the overall system. These kinds of complex systems have a potential impact on the railway operations and safety and reliability levels of the infrastructure and rolling stock. These railway assets are in turn subjected to degradation processes. For this reason, monitoring and diagnostics technologies are needed to detect the occurrence of faults and defects and to provide useful information to maintenance operators.

Below, the main monitoring parameters and aspects have been identified and described in order to support the design and the development of prediction models for asset management purposes.

All components of a signalling & control systems have to be designed in order to have an intrinsic internal safe diagnostic systems. However, several environmental factors and conditions could have influence on a correct functional status. For this reason, the external monitoring systems aim to achieve the following main objectives:

- A standardized collection of data and diagnostic information from the signalling and telecommunication components (legacy systems);
- Monitoring sensors with the aim of verifying (from an external point of view) signalling & control components;
- Additional non-invasive systems for the monitoring of the environmental variables/conditions that may adversely impact on the signalling & control system or on the overall railway availability (catenary, level crossing, *etc*).

11.2.1 ON-BOARD MONITORING

Nowadays, different kinds of signalling and control systems have been produced and installed on-board train by industrial companies. So, the monitoring and diagnostic systems have to be developed in order to assess the operative status of each single on-board component of the signalling and control system.

The common interest is focused to the complex equipment installed on-board train, especially onto locomotors (see Figure 23) where all the main functionalities of the signalling and control system have to be performed in order to increase the reliability and the safety of each train run.

Figure 23 Italian High Speed Train (ETR 500-“Frecciarossa”)

The on-board train locomotive equipment diagnosis is characterized by two main information sources:

- A continuous data flow
- The functional status of the system (alarm or no alarm)

As regards the operative condition of the components, a specific "log-file" related to the train run is created; it contains the following information:

- Timestamp (date and time)
- Train speed
- Covered distance by train
- Driver commands/input
- Others

This file is sent to a "data logger" which is able to collect and to process all the information contained in it and also to generate specific messages (i.e. SMS) to provide useful diagnostic information related to each single on-board component. The messages and the log-files are sent to the control centres in order to analyse the critical information contained in the log-files and to make decisions in order to mitigate the risk of faults and anomalies related to the on-board equipment under examination.

Currently, an innovative kind of on-board monitoring and diagnostics technology are the measurement trains (see Figure 24). These trains are only used to monitor in real time the status of the signalling & control equipment during their scheduled runs along railway lines.

Figure 24 Italian diagnostic trains: DIAMANTE (on the left) and ARCHIMEDE (on the right)

11.2.2 WAYSIDE MONITORING

Nowadays, different kinds of signalling and control systems have been produced and installed in the railway networks. So, monitoring and diagnostic systems have to be developed in order to assess the operative status of each single on-board component of the signalling and control system.

11.2.2.1 LEGACY SIGNALLING SYSTEMS

Existing signalling & control equipment is not always equipped with maintenance and diagnostic tools; the monitoring of the equipment functional status is required in order to cover this gap. In order to avoid impacting the system safety, the data collection processes have to be done in a non-intrusive way.

The most important components to be monitored of the signalling & control systems have been reported below:

- Point machines
- Signals (mechanical, colour lights, routing and speed, approach release)
- Track circuits
- Axle counters
- Others

11.2.2.2 BALISES

One of the most critical elements of the signalling system is represented by the balises (also named "Eurobalises"). A balise is used to transmit data from the track to the train on-board signalling equipment; the data sent provides the complete information needed from the wayside for train movement to be safely supervised so that the on-board system can calculate the safe speed profile and display the relevant movement authority to the driver.

The two main critical monitoring aspects related to the functional status of balises have been reported below:

- Installation of the balises on the track (both in terms of positioning of the balises along the line and of geometrical alignment with rails and sleepers) in order to guarantee correct data transmission between the balises and the train on board systems
- Signal quality in order to perform a preventive diagnosis to identify possible balises capturing problems

11.2.2.3 TRACK CIRCUITS AND AXLE COUNTERS

One of the possible solutions for the monitoring of track circuits and axle counters consists in a fibre optic system that is able to detect the train presence and speed. This is achieved by measuring how a train passing on the rail affects the light signal that passes through a rail-bonded fibre sensor. This information will be useful to support the signalling system in case of problems/failures in order to check the train presence inside the section. Fibre-optic sensors have found wide usage in railway applications due to their high sensing performance and small size. They allow measurements that are unfeasible or uneconomic with conventional electrical measurements. This is because electromagnetic interferences have no impact and, at the same time, they are not sources of electromagnetic interference. The fibre optic system will also allow monitoring of ambient temperature in order to detect particular risk conditions in indoor (such as fire and explosions in tunnels, *etc*) and outdoor areas related to low temperatures (such as snow, ice, *etc*).

11.2.2.4 LEVEL CROSSING CLEARANCE

Level crossings are considered a very critical component of the signalling system since they can be subjected to risks related to intersection with other transport infrastructure (i.e. roads). A main aspect of a level crossing monitoring system is the clearance of the area around the level crossing from any intrusion.

An inspection system should be able to perform the following functions:

- To inform the road traffic about an incoming train
- To monitor road traffic in order to inform the train driver about a potentially dangerous situation
- To inform road traffic that the situation is video surveyed and that the video can be used against him if he creates a dangerous situation

The required equipment includes:

- Masts with cameras (video and thermal) and scan area sensors
- Sensors on both sides of the level crossing to detect the presence of train
- Outdoor video screens to provide car drivers with dynamic information. This screen can included commercial spots to add to the return of investment and create a distraction for the car driver during waiting time
- Train traffic lights to inform the train drivers about risky situations
- Optoelectronics that allows the above system architecture to work also under the most extreme weather conditions

11.2.2.5 RADIO INTEGRITY DETECTION SYSTEM

In general, the need for radio signal quality measurement is a main requirement in a communication system for technical, legal and business reasons. In the railway context, the characterization of the quality of a voice signal is also fundamental in order to guarantee high safety levels for the train operations. Moreover, external electro-magnetic sources can generate interference that can cause severe impacts on the radio communication systems. The consequence of such interference could vary from the temporary loss of service to an infrastructure failure affecting multiple areas for an extended duration. For this purpose, radio integrity monitoring systems are needed in order to analyse in real-time radio signals, to detect and classify interference, and to notify through the railway signalling system. The system has to identify the source of interference (type, distance, *etc*), the intensity and the extension of the problem.

The system has to be able to perform the following tasks:

- Analysis of the speech signal
- Analysis of the quality of the data connection
- Analysis of the data connection during the transition between two different transmitters

In particular, the system has to be able to monitor the following aspects:

- Connection times
- Exchange connection error
- Loss rate connection
- Transmission times
- Periods of interference
- Recording times on the network

11.2.3 AN EXAMPLE OF AN ERTMS DIAGNOSTICS VEHICLE

Figure 25 ERTMS Diagnostics Vehicle

This special vehicle (MV ERTMS - Measurement vehicle for ERTMS Diagnostics), see Figure 25 and Figure 26, was built from a former passenger diesel coach, equipped with the measurement systems for measuring conventional signalling system and with ERTMS equipped lines, including specific measurements of wayside monitoring equipment and signals. The vehicle can be used for measurements of:

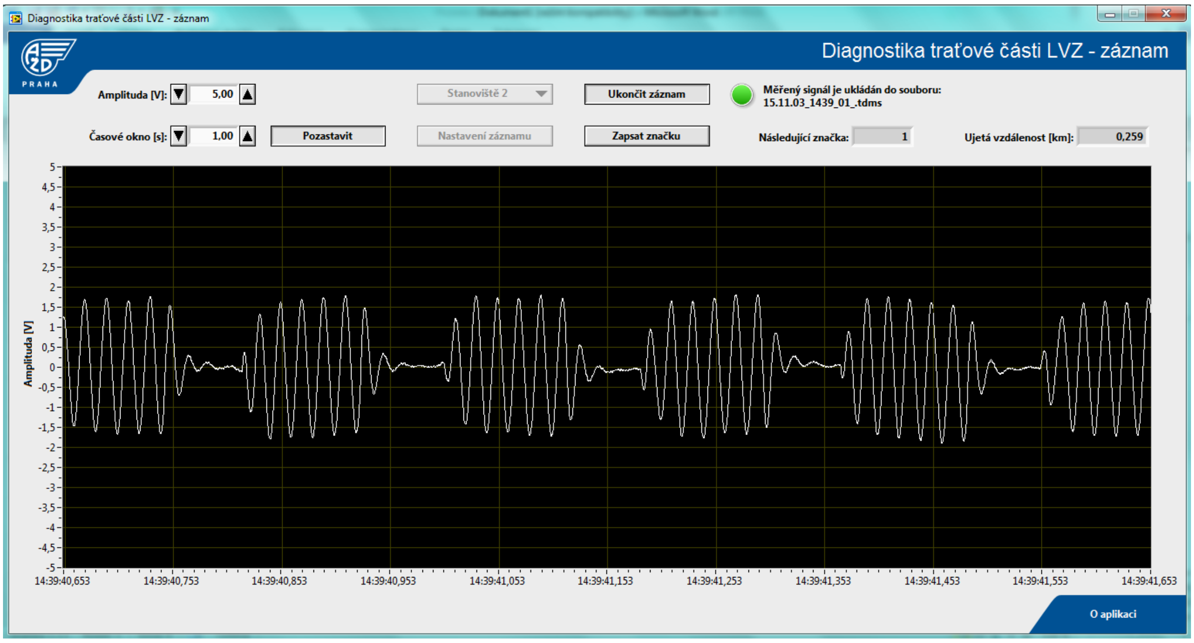
- Diagnostics of on-track portion of continuous train control system
- Diagnostics of on-track portion of ETCS
- Diagnostics of the level of radio signals
- Diagnostics of hot box detector
- Imaging of signals

Figure 26 Diagnostics equipment

MV ERTMS – DIAGNOSTICS OF ON-TRACK PORTION OF CONTINUOUS TRAIN CONTROL SYSTEM

- Signal from LS06 sensor and odometer signal are brought to a connector at the driver's cab, see Figure 27
- Measuring vehicle (2 modes):
  - data-recording mode – on-line logging of output voltage, odometer signal, and time; option of adding user markers
  - data-browsing mode – display of overall measured signal or just a part of the spectrum according to requested filter (50 Hz, 50/75 Hz, 75 Hz, 60 Hz), see Figure 28.

Figure 27 Driver's cab



Diagnostika traťové části LVZ - záznam

Amplituda [V]: 5,00

Časové okno [s]: 1,00

Měřený signál je ukládán do souboru: 15.11.03_1439_01_.tdms

Následující značka: 1

Ujetá vzdálenost [km]: 0,259

Figure 28 Measurement diagrams

MV ERTMS – DIAGNOSTICS OF ON-TRACK PORTION OF ETCS

- the measuring vehicle is equipped with mobile ETCS part (version SW 2.3.0d), which is approved as a test device for now;
- mobile part of ETCS is complemented by a diagnostic interface consisting of ODL (On-board Diagnostic and Logging) module;
- ODL module can be controlled from any computer, which is connected to data network in the measuring vehicle, where the necessary application is installed;

MV ERTMS – DIAGNOSTICS OF THE LEVEL OF RADIO SIGNALS

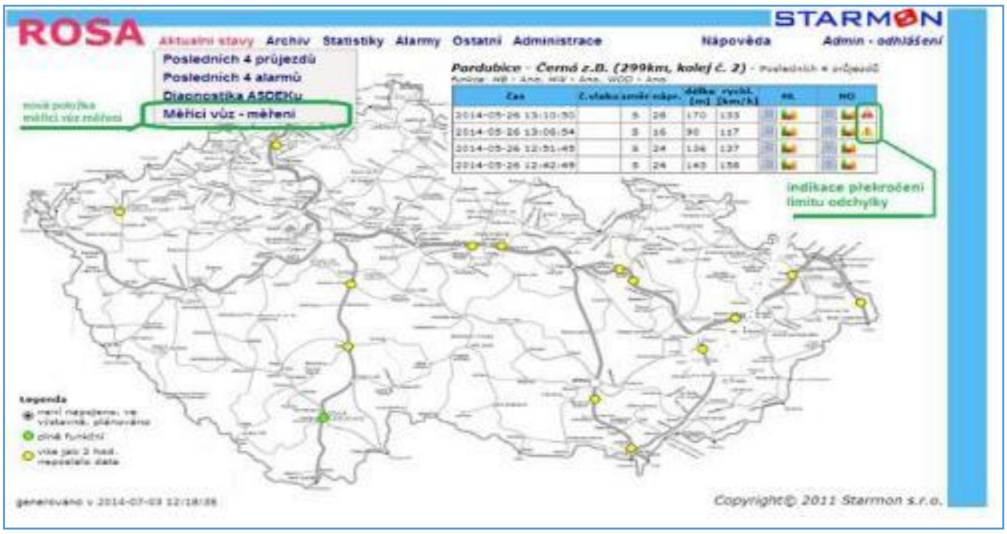
- measuring vehicle is equipped with antennas for measuring the level of radio signals:
- 4 GSM-R antennas for CW measuring – 4 measuring CMS receivers connected to odometer of the measuring vehicle, thus ensuring concurrent measuring and recording of 4 appropriately set up channels of separate BTSs each 10 cm driven distance, evaluation of EIRENE criteria for separate track section for -95dBm level each 100m track section with probability of 95%;
- 2 GSM-R antennas for measuring using MT2 terminal;
- VA42 antenna and 2 VA46 antennas for measuring and monitoring of analogue and local radio networks;

MV ERTMS – DIAGNOSTICS OF HOT BOX DETECTOR

- checking of hot box detector and hot wheel detector functionality, see Figure 29 and Figure 30;
- the basis are heating units, which simulate temperature of hot boxes and hot wheels;
- logging of the real temperature of the units together with GPS coordinates and time into data file and sending the file to ROSA server, where the data is paired with the measuring vehicle, see Figure 30;

Figure 29 Hot box diagnostics testing

Figure 30 Hot box detector indicator



Pardubice - Černá z.B. (299km, kolej č. 2)

Čas	Č.vlaku	směr	náp.	délka [m]	rychl. [km/h]	PK	HO
2014-05-26 13:10:50		5	26	170	133		
2014-05-26 13:06:54		5	16	90	117		
2014-05-26 12:51:45		5	24	136	137		
2014-05-26 12:42:49		5	24	143	158		

Figure 31 Map with diagnostic's results

MV ERTMS – IMAGING OF SIGNALS

- Images of signals from beforehand defined distances are gained by the means of camera systems located at driver's cab;
- Acquired data are saved into a database in the form of graphic files, clearly assigned to the given object, and are available to users through a web application, see Figure 32;

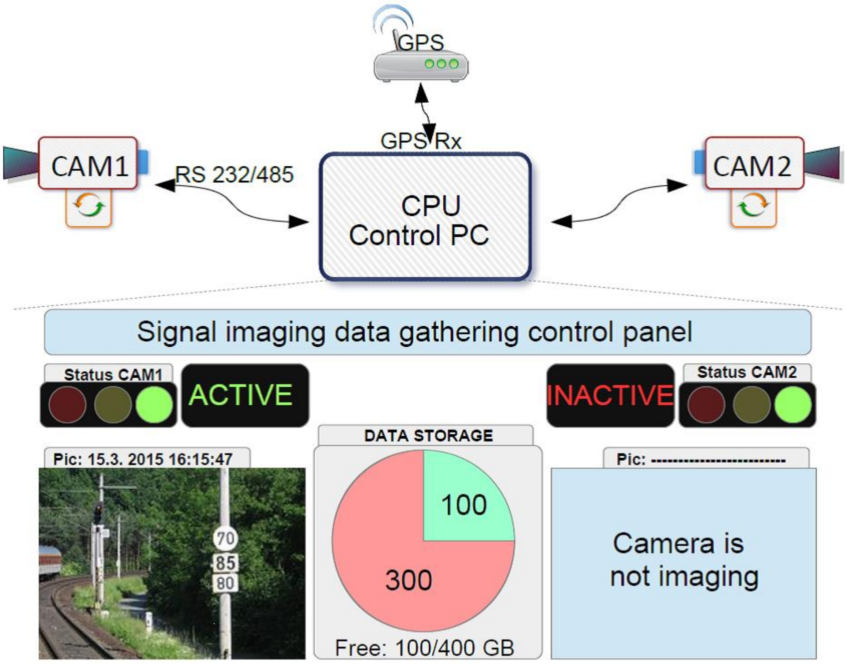


Figure 32 Screenshot of the signal imaging

The camera system collects snapshots of signals on the basis of requirements sent by control software running on the control PC. Snapshots are generally taken at the following distances from the object in question:

1. 100 metre distance from the signal
2. Distance equivalent of 10 seconds ride of a rolling stock at the maximum allowed speed on the track section
3. Distance equivalent of 7 seconds ride of a rolling stock at the maximum allowed speed on the track section
4. 10 metre distance from the signal (the distance value is not fully binding, it can change at the time of system testing depending on the possibilities of supplied technologies)

Thus the distances at which an object is captured vary significantly from about 0.5 km to 10 m. This puts significant requirements on the camera system (lens with adjustable focus, adjustable bracket for when the pictured object is in a bend outside of the current direction of vehicle movement). Therefore the control software has to set up the camera system so that it is able to take a snapshot (or sequence of 4 snapshots) of the object at the right moment, save this snapshot and reliably pair it with the object. It is necessary to create a corresponding database storage and application, which will provide the measured data by the means of a website to authorised users.

Data collection system for snapshotting of signals will be placed in a vehicle as indicated in Figure 33.

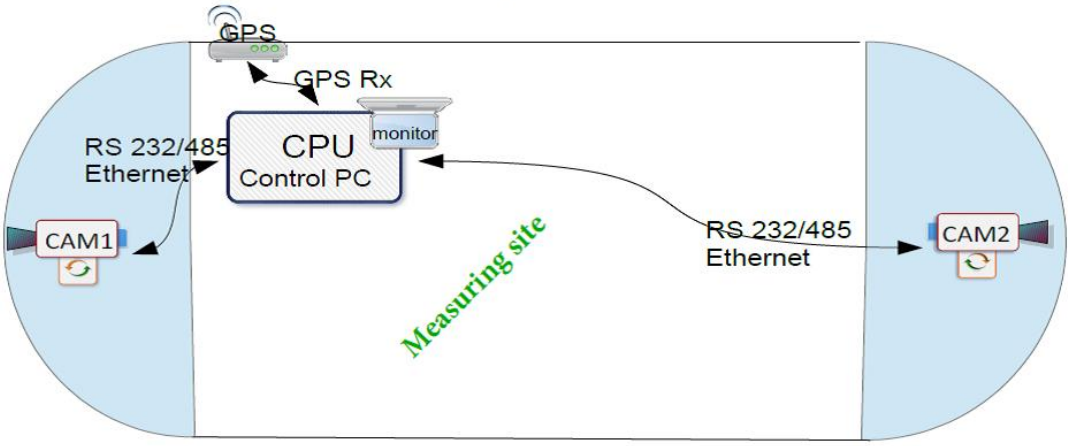


Figure 33 Location of the system in a measuring vehicle

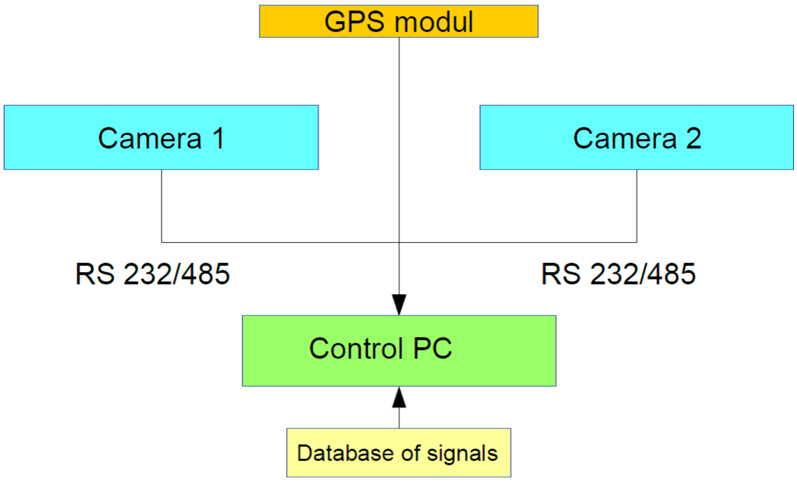


Figure 34 Role of control PC

The contractor will provide a database of signals, which will be populated by snapshots, see Figure 34. The queue is fed from the system using an automatic algorithm based on assessing image location using a GPS module.

The data is provided in a structure illustrated in Table 11.1.

Table 11.1 Illustration of data structure.

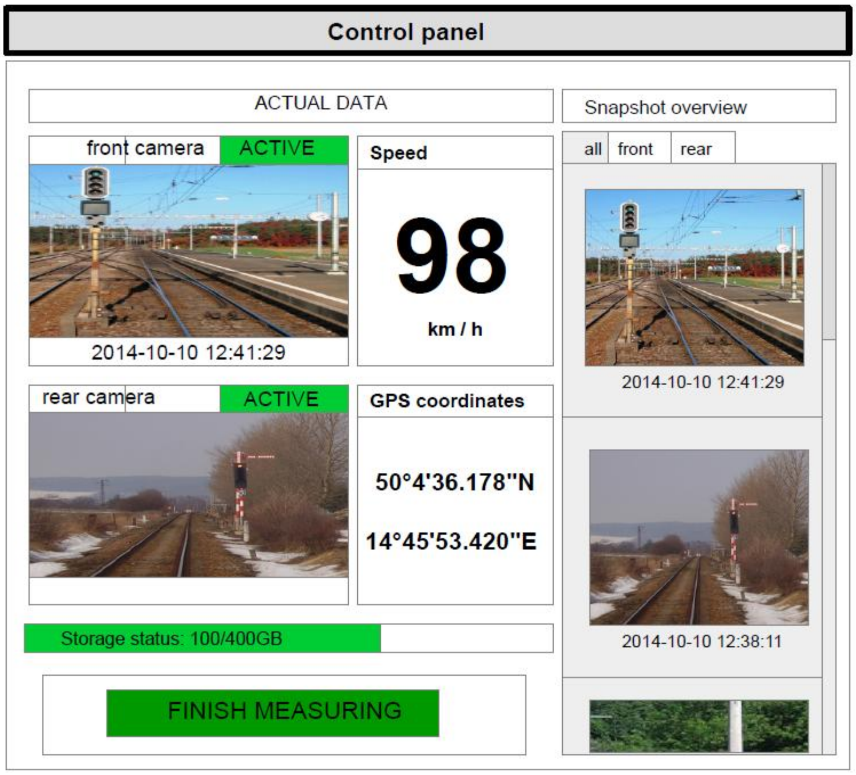
codenov	Name	Type	Loc.code	km	basic_superline	gps	
7009000000294	Český Brod 1L	Entry signal	150134	375.621	66500 - B501021 1	50°4'54.211"N	14°53'3.096"E
7009000000295	Český Brod 0L	Entry signal	150134	375.621	66500 - B501342 0	50°4'54.219"N	14°53'2.641"E
7009000000296	Český Brod 2L	Entry signal	150134	375.621	66500 - B501342 2	50°4'54.424"N	14°53'2.806"E

Each signal is linked through the “codenov” column to the complete coordinates at which the snapshot was taken. The distance (time/length) from signal is stored as separate data, see Table 11.2

Table 11.2 Coordinates of snapshot

codenov	gps	
7009000000294	50°4'54.361"N	14°53'3.540"E
7009000000295	50°4'54.370"N	14°53'3.085"E
7009000000296	50°4'54.573"N	14°53'3.245"E

The main screen of the application, see Figure 35, indicates status of both cameras, displays the last taken snapshots for each camera separately, and provides an overview of free storage space. A notification message is displayed when reaching 85% of the capacity. The right column allows displaying snapshots sorted by time with the possibility to filter per camera, which took the snapshots. Each folder (all, front, rear) will display the last 20 snapshots.



front camera: ACTIVE, 2014-10-10 12:41:29

rear camera: ACTIVE

Speed: 98 km / h

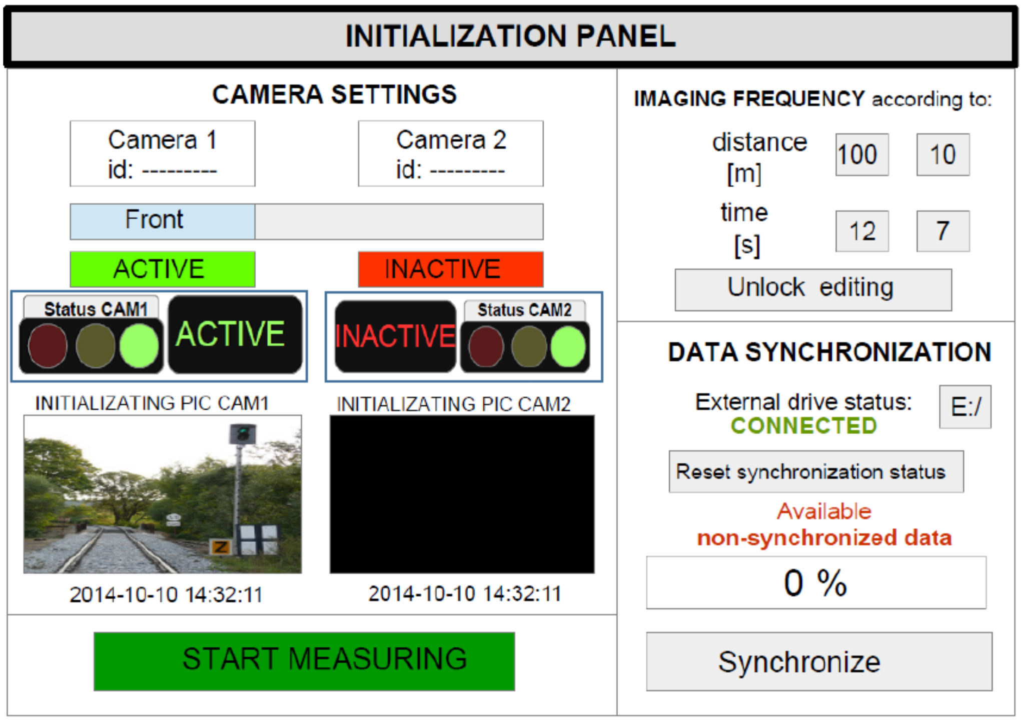
GPS coordinates: 50°4'36.178"N 14°45'53.420"E

Storage status: 100/400GB

Snapshot overview: 2014-10-10 12:41:29; 2014-10-10 12:38:11

Figure 35 Control panel view

After pressing the “**Finish measuring**” button, a confirmation dialogue is displayed and after confirming, the application returns to the initialisation screen, see Figure 36. Finishing can also happen automatically due to lack of free storage space (less than 1 GB), because the application’s ability to carry out its operation would be threatened.



Camera 1
id: ---------

Camera 2
id: ---------

Front

ACTIVE

INACTIVE

ACTIVE

INACTIVE

2014-10-10 14:32:11

2014-10-10 14:32:11

IMAGING FREQUENCY according to:

distance [m] 100 10

time [s] 12 7

External drive status: **CONNECTED** E:/

Available
non-synchronized data

0 %

Figure 36 Initialization panel view

The integrated database structure in the application is illustrated in Figure 37.

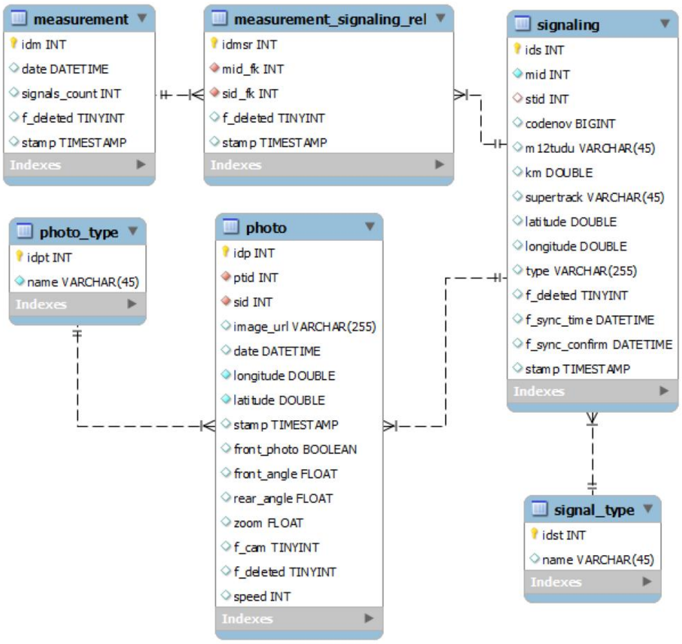
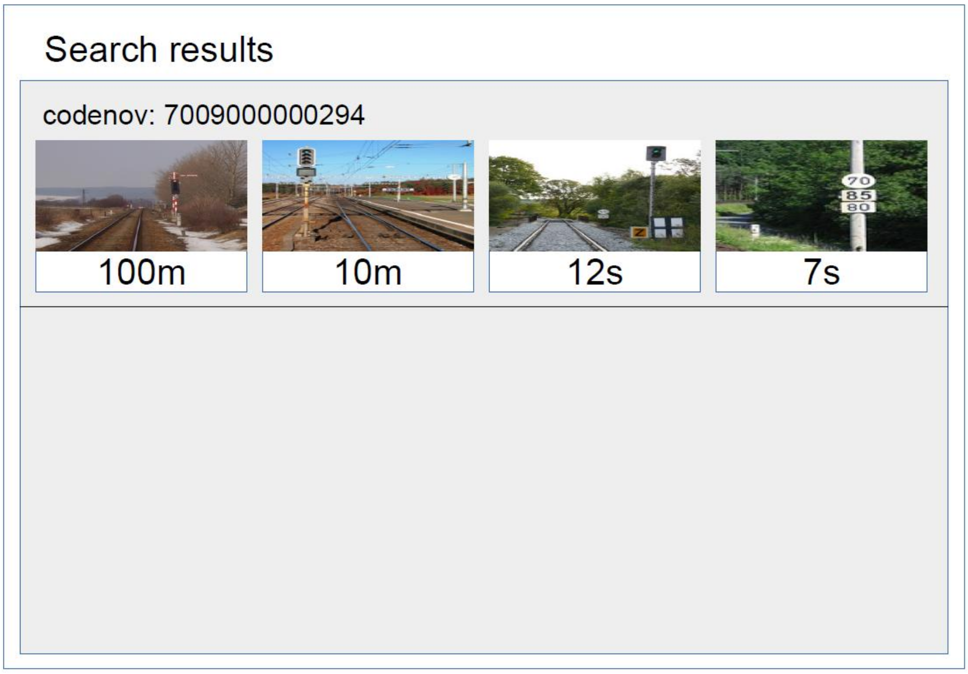


Figure 37 Integrated database structure

A user gets an overview of search results after searching the database according to entered parameters, see Figure 38.

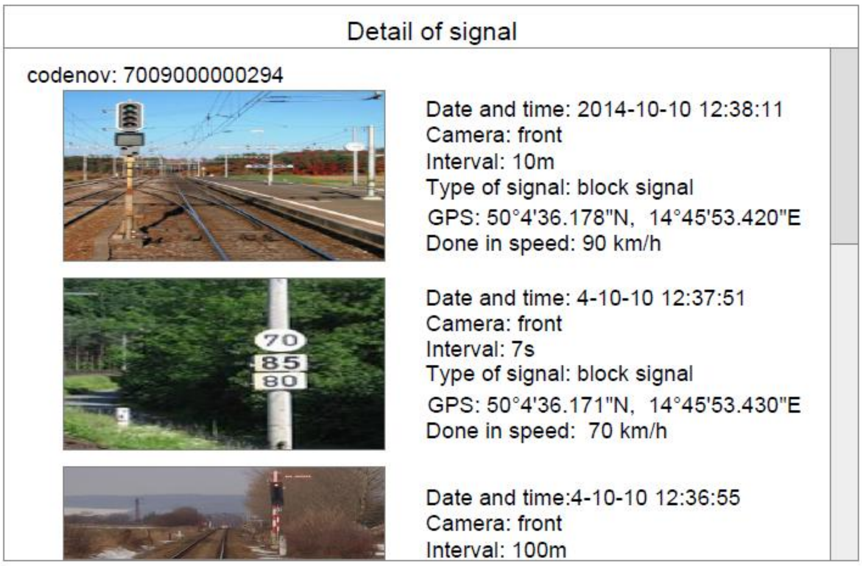


Search results

codenov: 7009000000294

Figure 38 Example of search results

After clicking a selected snapshot of any signal or its label (codenov), a detail of this signal with detailed description of every snapshot taken for this signal is displayed, see Figure 39.



Detail of signal

codenov: 7009000000294

Date and time: 2014-10-10 12:38:11
Camera: front
Interval: 10m
Type of signal: block signal
GPS: 50°4'36.178"N, 14°45'53.420"E
Done in speed: 90 km/h

Date and time: 4-10-10 12:37:51
Camera: front
Interval: 7s
Type of signal: block signal
GPS: 50°4'36.171"N, 14°45'53.430"E
Done in speed: 70 km/h

Date and time:4-10-10 12:36:55
Camera: front
Interval: 100m

Figure 39 Example of detail of signal

A detail of a specific snapshot is displayed after clicking on it. It is possible to then choose the most suitable snapshot from the taken sequence of snapshots, see Figure 40. The main (selected) snapshot is framed with a colour rectangle. It is possible to set the direction of the snapshotted signal at the bottom part of the screen by dragging with a mouse. This data then serve to improve quality of future snapshots.

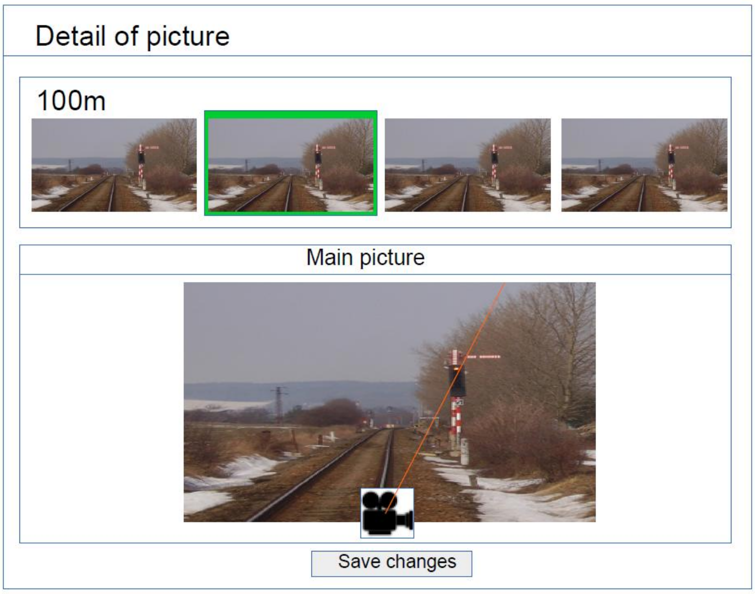


Figure 40 Example of detail of picture

MV ERTMS – MONITORING OF FUNCTIONALITY OF TRACK CIRCUIT WHILE USING PROGRESSIVE SANDING DEVICE FOR ROLLING STOCK TYPE KOVA-03D

A sanding device is a modern, environmentally-friendly system, which with its pneumatic method ensures high operational reliability and eliminates excessive sanding (both one-shot and continual discharge of sand). The device ensures an increased adhesion coefficient between wheel and rail during acceleration and braking, thus increasing active safety of the train set. The action is based on the principle of grinding used sand granulate, which creates so-called “sand nests” both on wheels and the rail. These “sand nests” are used also by the following wheels of the set and brake without anti-slip effect. Large-scale tests of the International Railway Union have shown that sand nests are after 1st overrunning so stable that there have been no changes of in size of the spreading granulate or sand nest after the 10th overrunning. The efficiency relates to an optimal amount (defined by TSI) and quality of the used sand. The required parameters are defined by Directions of infrastructure manager for ensuring smooth and safe railway traffic no. 1/2008, and Commission Decision 2006/679/EC of 28 March 2006, annex A, appendix 1, art. 4.1.1.

The measuring vehicle is equipped with a sanding device for rolling stock type KOVA-03D for measuring the amount of used sand. It allows testing if conductivity prescribed by a standard is achieved during the right operational and environmental conditions for sanding.

Construction and design allows operating in environmental conditions defined in temperate climate as per ISO EN 50125-1 with the following parameters:

Temperature class outside of the vehicle:	–30 °C to +40 °C
Value the temperature can drop to for 6 hours	–33 °C
Range of the line's altitude	A 1 (up to +1,400 m)
Outside humidity yearly average of relative humidity	75% continuously for 30 days in a year
Max. relative humidity outside of the vehicle	100%
Max. absolute humidity in tunnels	30 g/m^3
Rain intensity as per class 5K3 ISO EN 60721-3-5	6 mm/min
Max. wind speed	35 m/s (in extreme cases up to 50 m/s)
Max. relative humidity inside the vehicle	80%
Max. absolute humidity inside the vehicle	13,75 g/m^3
Max. thickness of snow layer above the upper surface of the rail	140 mm
Max. water level above the upper surface of the rail	50 mm

Conductivity parameters of the rail are measured during sanding. This is how the correct functionality of track circuit is evaluated.

12 MONITORING OF OVERHEAD CONTACT LINE SYSTEM

Railways equipped with an electrification system need power supply systems to be safe, reliable, cheap and maintainable. Figure 41 shows the overhead contact line system (OCL). Such systems can be classified based on the different kinds of electric current:

- Direct Current (DC): Has been used for many years and is considered to be more simple for railway traction purposes;
- Alternating Current (AC): Provides better performance over long distances and is cheaper to install. It is however considered to be more complicated to control at the train level.

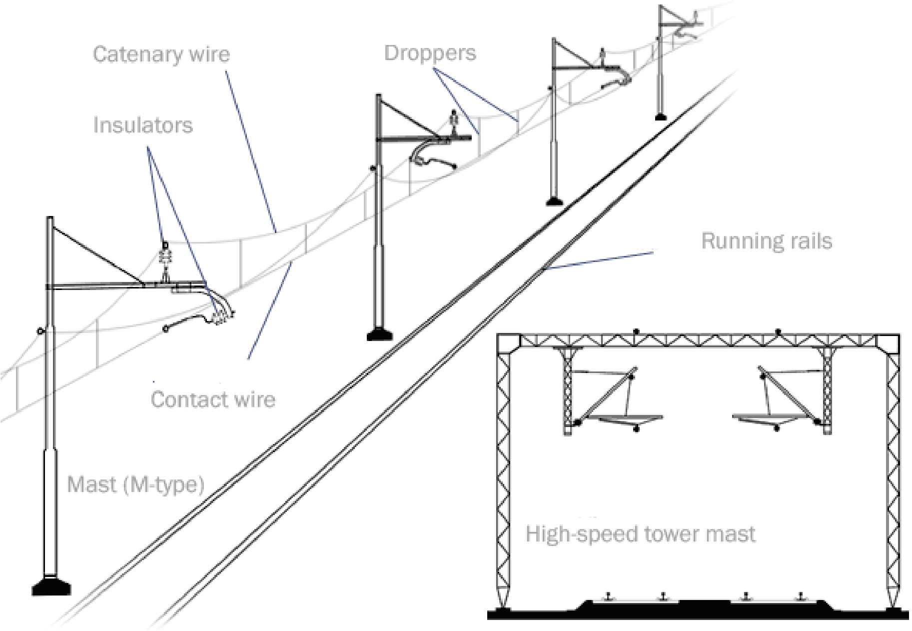


Figure 41 The railway OCL system and power supply systems

Along the railway track, power transmission is performed by means of an overhead contact line (OCL) or at ground level through an extra third rail positioned close to the running rails. Commonly, AC systems use contact wires, DC can use either a contact wire or a third rail. The OCL systems require at least one collector (denoted “pantograph”) attached to the train to provide continuous contact between train and contact wire.

The return circuit is through the train, via the running rail and back through the overhead lines to the substation. The rails used for return circuits are at earth potential and are connected to the substation.

In the following sections the main critical components of the OCL and power supply systems have been described in order to identify the most common typologies used along railway lines and to highlight the main parameters and defects to be monitored for condition-based maintenance purposes.

12.1 CONTACT LINES

In the railway context, the OCL and related mechanics of power supply are among the most critical phenomena. The wiring and the interaction with the pantograph of running trains can have severe impacts on reliable (and safe) operations. The mechanics of power supply wiring is intricate. The wire must be able to carry the electric current, remain in line with the route, and withstand pantograph loading, wind and other hostile weather conditions.

OCL has a complex geometry, nowadays usually designed by computer, as the catenary wire must be curved in a certain way to hold the contact wire (by the droppers) as straight as possible during train passages. Many kinds of catenary suspension system have been used and their forms depends on:

- Electric voltage (AC/DC)
- Age
- Location
- Train speed

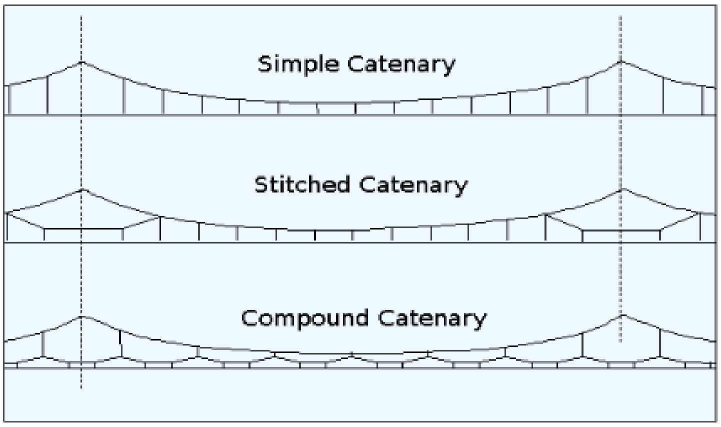


Figure 42 Catenary system typologies

The complexity of the catenary topology (see Figure 42) depends on train speed. Higher speed typically requires a more complex geometry. Alternatively, a simple catenary could be installed also along high-speed lines, but the support posts must be very close together. The same holds for lines with severe wind conditions.

Modern installations often use the simple catenary, slightly sagged contact wire to provide a good contact: it has been found to perform well at speeds up to some 200 km/h.

The optimal designed overhead contact wire (see Figure 43 and Figure 44) must have the following characteristics:

- To maintain the contact wire height between minimum and maximum value and with a permissible gradient;
- To maintain the contact wire height also during train transit and prevent excessive vibrations;
- To maintain uniform elasticity;
- To maintain the contact wire following a symmetric zigzag schema referred to the track axle (stagger);
- To be reliable towards the transversal wind effects.

The contact wire doesn't follow the lateral position of the railway track exactly. Instead it crosses the rail line from side to side. This is referred to as "stagger" (also called "polygonation"), see Figure 44.

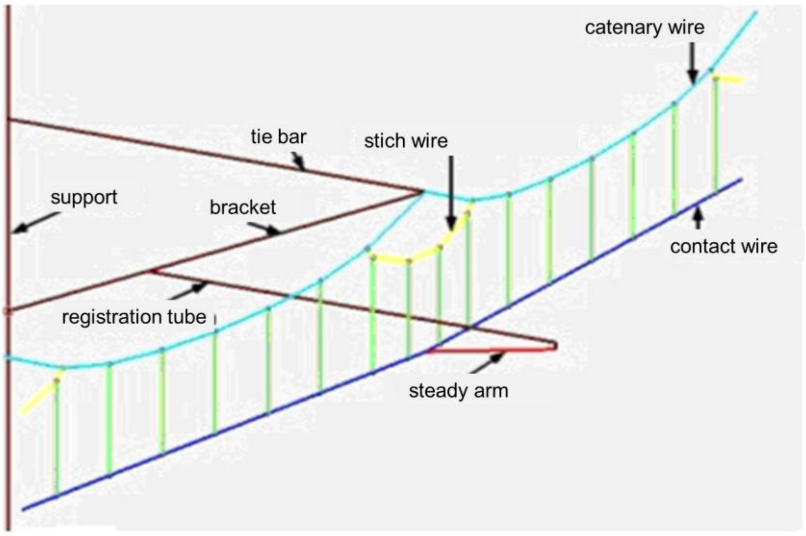


Figure 43 Catenary suspension structure

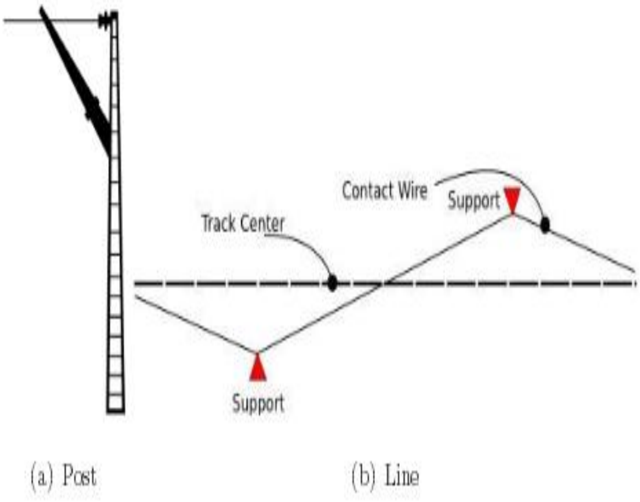


Figure 44 Illustration of a staggered contact wire

12.2 PANTOGRAPH

The pantograph (or "pan") is an apparatus mounted on the roof of an electric train or tram to collect power through contact with an overhead catenary wire. It is a common type of current collector. The term stems from the resemblance of some styles to the mechanical pantographs used for copying handwriting and drawings.

The main aim of a pantograph is to collect the electrical current from the catenary cable system and to transmit it to the train traction system. The differences in train performance and speed significantly affects the required pantograph design and construction, as resumed below.

Pantographs can be categorized as (denotation refers to side view):

- Double arm (also named diamond–shaped), usually heavier, requiring more power to raise and lower, but may also be more fault-tolerant)
- Single arm (also named Z-shaped)

Pantographs can be categorized as ((denotation refers to front view):

- T-shaped
- Y-shaped

From the point of view of the control mechanic systems, pantographs can be divided into:

- Pneumatic pantograph

- Electrically driven pantograph

12.2.1 PANTOGRAPH COMPONENTS

A pantograph consists of a collection of bodies and mechanical elements attached to a railway wagon moving along the track. Due to the structural stiffness of the pantograph versus the contact lines, the main components that compose the pantograph can often be considered as rigid bodies. These bodies are connected by a set of kinematic joints that control the relative motion, and by a group of additional rigid and/or flexible elements. These elements are used to transfer relevant internal forces resulting from the interaction among bodies of the system.

The pantograph main components can thus be divided in the following categories:

- Basic rigid elements
- Active elements
- Passive elements
- Joints (prismatic, revolute and spherical)
- Sensors and actuators
- Constraints and drivers
- Force elements

12.3 DEFECTS AND CRITICAL FAILURES OF PANTOGRAPHS

Dynamical interaction between the moving pantograph and the flexible structure of the overhead contact line causes significant fluctuations in contact forces between the sliding bows surfaces and contact wire.

Further, loss of contact between pantograph and contact wire may produce arcing that can lead to excessive wear and/or overheating of the sliding surfaces. This will reduce the mechanical and electrical reliability of pantograph, catenary, and train power equipment.

Potential failure modes can be divided into three main categories:

- Cracking
- Wear
- Plastic deformation

The pantograph sliding surfaces (head assembly) performance could be influenced by:

- Mounting conditions
- Mechanical wear[51]
- Electromechanical wear[51]
- Weather conditions
- (Variations in) positions of contact with the contact wire
- Crack formation

The mounting conditions could be different related to the actual railway track characteristics and the power equipment of the trains (urban, regional, high speed, *etc*).

Wear is an inevitable effect on pantograph-OCL systems: this phenomenon usually determines the lifetime of the collector strips on the pantograph that form the interface towards the contact wire.

The phenomena of wear and crack formation are influenced by many parameters:

- Electrical current
- Train speed
- Dynamic and quasi-static loads (normal and frictional force, sliding conditions)
- Atmospheric conditions (air temperature and humidity, rain, frog, crosswind, snow, ice formation on contact wire, solar exposure, *etc*).

Compared with the atmospheric conditions, the contact strip experiences a lower friction coefficient and resulting wear rate due to the lubricating (and cooling) effect the water. Note however that excessive water (and in particular frost/ice) it can increase the frequency of the electric arcs.

The strip surface may be oxidized under the water fog ambient conditions, as in the oxygen environment: oxidative wear and arc erosion are the dominant wear mechanisms in water fog environment during the electrical sliding processes.

During working conditions, the contact strip is sliding on a macroscopically flat surface of the contact wires (see Figure 45). The consequences are wear tracks parallel to the sliding direction and also oscillatory movements. A contact that is always at the same point of the pantograph is therefore not reliable since it will result in deep wear grooves on the contact strip.

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[51] V Björk et al: Carbon Strip Challenge – Designing new carbon strips for better railing, 48 pp + appendix 3 pp, 2010 (http://www.chemeng.lth.se/ket050/Finalreport2010/Carbonstrip.pdf)

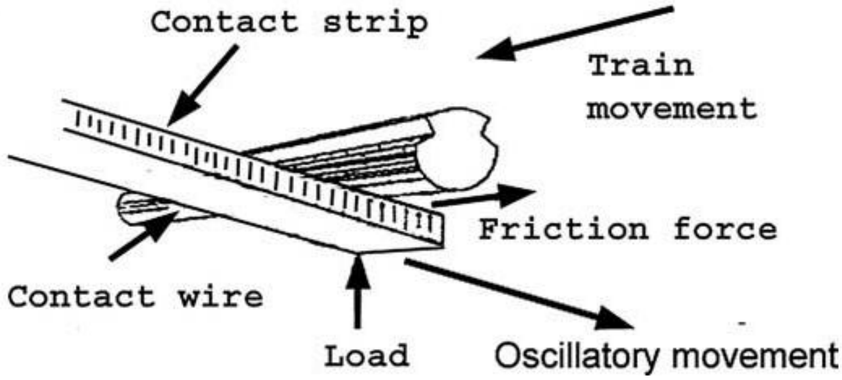

Figure 45 Detail of the power collection system: the sliding movement and active forces

The regions of the pantograph that are in contact with the contact wire are crucial for the system. The vast majority of problems can occur due to wear and deterioration on the surface of pantograph. The pantograph surface can be divided into three specific regions (see Figure 46), named based on the effect of the contact loads. These are:

- **Region n°1 ("Fault region")**: This region corresponds to the horns and the ends of the pantograph. If any contact occurs here, it causes enormous damages. Breaking or rupture can occur on the pantograph and the catenary and contact can be cut off.
- **Region n°2 ("Dangerous region")**: This region is between the fault region and safe region. Having a contact in this region does not directly lead to major problems, but is an undesirable condition and an indication that the system is not well adjusted.
- **Region n°3 ("Safe region")**: This region is the part of the contact strip intended to be in contact with the pantograph.

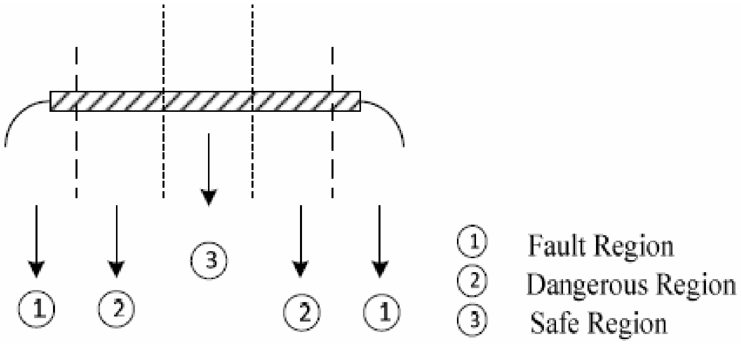

Figure 46 Indication of the main operative regions of the pantograph contact strip

12.4 MONITORING SYSTEMS

The catenary and power supply systems are complex systems. To be able to provide an overview of suitable monitoring measures, they have to be divided into the different components that play a key role in safe and reliable operations of the infrastructure and rolling stock. Moreover, the related railway assets are subjected to degradation processes. For this reason, the installation of the monitoring and diagnostics technologies is needed in order to detect the occurrence of faults and defects and also to provide useful information to maintenance operators. Reported information can also be used to support design and the development of predictive models for asset management purposes. In short, periodic condition monitoring, fault detection and pre-estimation are extremely important in the electrical railway systems.

The electrical energy for trains must be continuous and uninterrupted. So, the interaction and mechanical contact between the pantograph and the contact wire must be ensured at all instances in time. Many different kinds of monitoring and diagnostics systems exist to detect the presence of faults/defects on the catenary wire, the contact wire and the pantographs of operating trains in. In the following two subsections, the innovative wayside and on-board monitoring and diagnostics systems for the OCL and power supply applications in railway networks have been described, adding deeper details about the monitored parameters and applied technologies.

12.4.1 EXAMPLES OF WAYSIDE MONITORING SYSTEM

The efficiency of the power collection system depends on the electrical contact and the characteristics of materials of the wire and pantograph strip (conductive performance and wear resistance). Currently, the wayside monitoring systems are used to detect the faults and defects on the catenary wire, overhead contact wire and the pantograph elements related to the running trains. Monitored parameters include

- Contact wire uplift
- Contact force (upward force-see Figure 47)
- Contact carbon strip wear
- Pantograph integrity
- Bow (position, inclination, temperature)
- Electric arcing

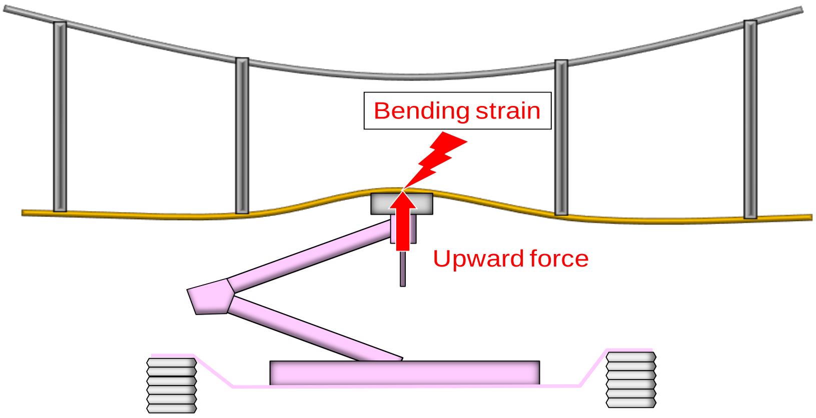

Figure 47 Bending strain of the overhead contact wire caused by train transit

The horizontal movement of the pantograph basically depends on the speed of the train, the elasticity on the contact wire and dynamic characteristics. The vertical movement of the pantograph depends on the lifting force applied by the actuator to the pantograph. Basically, they have been composed by different kinds of sensors and devices (such as accelerometers, strain gages, load cells, *etc*) installed on the support and suspension systems. In particular, the optical-no contact wayside inspection systems have been used to detect possible structural damages and geometric anomalies of the pantograph of the trains that pass underneath.

Thermal scanner and high-speed & high-resolution video cameras have been used to monitor the following parameters related to the main elements of the pantograph (see Figure 48):

- Cracks, grooving and chipping on the carbon strip
- Carbon thickness (wear)
- Carbon angle
- Horn alignment
- Uplift pressure (lifting force)
- Train speed

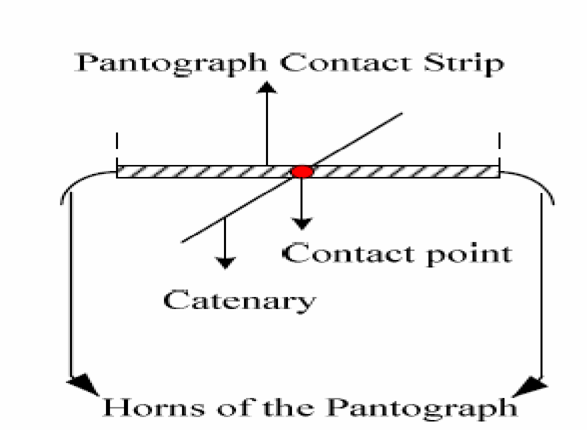

Figure 48 The main pantograph components to be monitored

Moreover, a wayside inspection technology has been applied to monitor and control the condition of the OCL/contact wire by collecting data and measures of voltage and drained current into the overhead line. This kind of monitoring system has been essentially composed by the sensing unit (dropping resistor, voltage sensor, *etc*) has been directly mounted at the catenary support, whereas the processing unit designed for easy mounting in an adjacent substation.

12.4.2 EXAMPLES OF ON-BOARD MONITORING SYSTEMS

Due to both the rolling stock speed and performances improvement and the traffic volume growth, the application of on-board train monitoring systems has become important in order to make railway networks safer and more reliable. Several kinds of on-board monitoring systems have been used on diagnostics trains and specific measurement vehicles. These can run along the railways lines collecting a great amount of data and information that is sent to a control centre for maintenance planning purposes.

As in the wayside monitoring systems solutions, mainly optical – no contact technologies (such as scanners, cameras, *etc*) have been installed on-board trains (on the upper part of the locomotives). These systems can be integrated with other common measurement systems (e.g. load cells, accelerometers *etc*) to provide a higher precision in the status monitoring of catenary, pantograph and power supply systems.

The measurement trains has on-board monitoring and diagnostics technologies for the OCL. These vehicles are only used to monitor the status of the OCL and power supply systems in real time during their scheduled runs along railway lines.

UIC Leaflet 791-2 describes the diagnosis of the OCL condition. The parameters have been divided into four parameter groups

- Geometrical parameters (height, stagger, critical points, wear, sag, gradient, longitudinal sizes, uplift, uplift uniformity)
- Electrical parameters (voltage, current, losses of contacts, arcs, electric warming and thermal imaging)
- Mechanical parameters (forces, elasticity, elasticity uniformity). Here acceleration measurements can be employed to detect dents on the contact wire. Such dents affect the contact in the point and thereby significantly increase wear and/or arcing.
- Auxiliary data (temperature, weather condition, wind, track layout, operating condition of the OCL, characteristics of the employed vehicle, performance of the measurement devices and diagnostic fixed systems along the line)

Main parameters (related to main defects classes) to be monitored by on-board optical-no contact technologies are:

- Changes and corrosion (on main catenary infrastructure devices);
- Broken and/or bulged droppers
- Dropper slant
- Broken or missing insulator parts
- Mast
    - Presence of cantilevers (distance and spatial)
- Contact Wire Geometry
    - Wire height
    - Wire stagger
    - Wire wear (residual thickness)
    - Critical points
- Mechanical
    - Force
    - Uplift
    - Elasticity
    - Pantograph pan vertical acceleration
- Electric Analysis
    - Overhead line voltages

    - Line drained current
- Electric Arcing
    - Arc location (kilometric position)
    - Arc duration
    - Arc intensity
    - Sum of all arcs duration
    - Number of all arcs (having minimum duration of 0.015s)
    - Largest arc duration
    - Percentage of arcing
- Auxilary
    - Temperature

12.5 EXAMPLE OF OPERATIONAL FUNCTIONAL TEST

For ensuring the system pantograph/contact wire, the DB Netz AG realized functional tests. In performing the functional tests, the shared measuring systems are to be observed. The functional test is considered complete when the documented recordings and data are evaluated.

12.5.1 FUNCTIONAL TEST F1

The functional test F1 checks the position of the contact wires. For the F1 test inductive sensors are used (as shown in Figure 49). These are mounted at the required distances from the middle of the carbon strips.

Figure 49 Inductive sensors

The required distances are in the DB tests set at 600 mm, 750 mm and 800 mm.

(1) For contact positions with values less than 600 mm there is no need for action.

(2) For contact positions with values exceeding 750 mm, the contact wire system must be checked immediately.

(3) For contact positions with values between 650 mm and 750 mm, a check of the contact wire system must be scheduled.

12.5.2 FUNCTIONAL TEST F2

The functional test F2 checks

- Lateral position of the contact wire (catenary polygonation)
- Grade of the registration arm and the steady arm
- Cross span bridge.

Two kinds of a catenary suspension must be checked as demonstrated in Figure 50. The short suspension should in the DB regulations have a gradient of 20 mm to 150 mm from the middle. The long suspension should have a falling gradient of 20 mm to 150 mm from the middle.

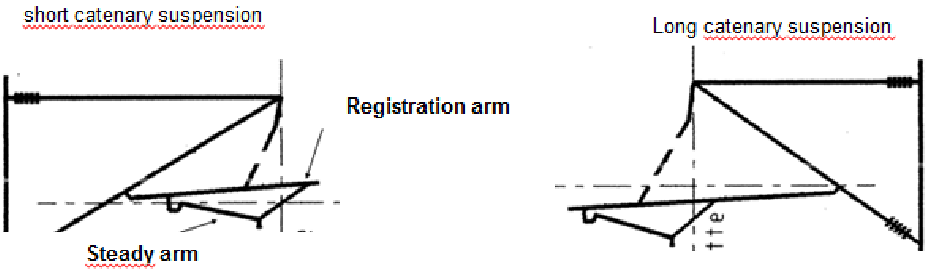

Figure 50 Catenary suspension

The distance between catenary and the track from the cross span bridge must be between 50 mm to 450 mm, as indicated in Figure 51.

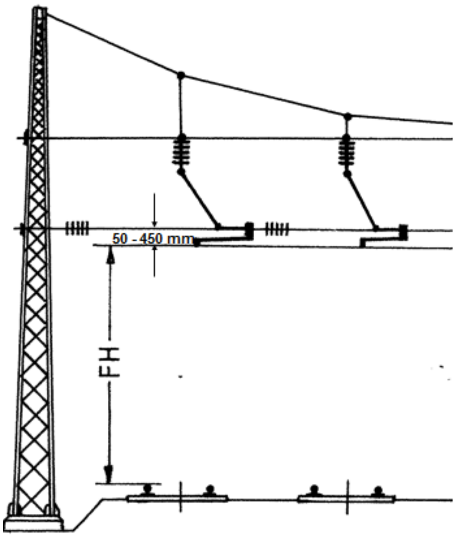

Figure 51 Bases of the cross span bridge

For the implementation a video unit is used. This allows observation of the catenary and pantograph during a measurement run. The device consists of a camera, a computer with an exchangeable hard disk and an illumination system.

The camera signal can be synchronized with measured data and recorded in digital form on hard disk of the PC for later analysis.

During playback mode user-friendly search functions are implemented. Scenes can be found based on a given track number and kilometre. Horn contacts can be accessed directly.

12.5.3 FUNCTIONAL TEST F3

The functional test F3 checks the catenary wire height at level crossings and other critical points. Critical points are track section with heights below 5.10 m and heights at crossing levels below 5.75 m.

The DB Netz AG uses a contact-free measurement system. The measurement principle is a double laser scanner based on laser radar using the phase shift method.

12.5.4 FUNCTIONAL TEST F5

The functional test F5 investigates catenary wire wear. The measuring distance when the continuous measurement starts shall not exceed 10 mm. The catenary wire may generally not have wear that exceeds 20% of the nominal cross section area.

The measuring principle is indicated in Figure 52. The laser head produces a light profile, which is detected by the camera sensor. The shadow caused by the contact wire is detected and used to determine contact wire wear.

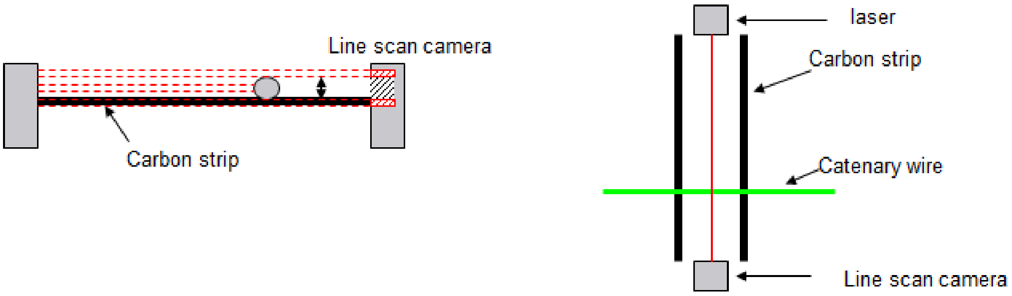

Figure 52 Measuring principle F5

12.5.5 FUNCTIONAL TEST F6

The functional test F6 checks the fluctuating force between catenary and pantograph. It is an important factor for assessing the overhead line system and assessing the interaction of pantographs with the overhead line system.

The function of the moving contact point is to ensure an uninterrupted, trouble-free transfer of electrical energy from the overhead line system over the pantograph to the running train. The contact must be such that the operational wear on the catenary and the carbon strips of the pantograph is as low as possible. On the other hand loss of contact may cause arcing, which may be very detrimental. This requires the contact force to be kept within specific limits. Too high a contact force results in increased wear due to abrasion and high dynamic stressing. Too low a contact force causer increased wear due to contact erosion through arcing.

13 CONCLUSIONS

13.1 KEY FINDINGS OF D4.1.1 OF IMPORTANCE TO THE CURRENT INVESTIGATION

The report D4.1.1 gives an overview, which technologies are today available and can be introduced within a short time into the network. Furthermore the report points out the possibilities to avoid failures and defects in the infrastructure by using available technologies able to monitor the status of components and systems. The difficulties of a migration strategy are also highlighted in the report, since all solutions need their own infrastructure for energy supply and data transmission. Based on the latest innovation programs funded by the EC, the first products have come to the market. These are smaller, cheaper, less energy consuming and WiFi/GSM compatible.

The common understanding of the infrastructure managers (IM) is that the economics of maintenance must be improved to be competitive to road/water/air. Reflecting on the needs of IM, the targets for the developments in the C4R-Project are described. The additional requirements are: low cost, simple use, maintenance free. The data should be able to be processed into diagnostic information so that failure prevention and a reliable maintenance forecast can be done. In this context it should be noted that the whole monitoring strategy must be a part of the business case “infrastructure management”.

Another problem is the diagnosis platform and the assessment of measured monitor data, which is often underestimated. This topic was not in the focus of the report, since it is very often strong coupled with company IT policies.

13.2 MONITORING STATUS OF VEHICLES AND WHEEL/RAIL INTERACTION

The current report details key parameters for monitoring status of vehicles including wheel/rail interaction. In many cases the parameters that would be required for a stringent status assessment are not directly available, but need to be derived indirectly. Further, the vehicle status evolves over time, which puts demands on continuous monitoring.

The report approaches the topic by identifying key areas of monitoring that are presented in separate sections. It then outlines the key parameters that relate to safe, reliable, cost-efficient and environmentally friendly operations. This contrasts to how these parameters can be employed to describe the current status and how they relate to what is monitored today and what is possible to monitor.

The chapter provides a solid foundation to build from when current monitoring strategies are to be enhanced (as will be made in deliverable D4.1.3) – the chapter provides both suitable aims and potential challenges for such an enhancement.

13.3 MONITORING OF RAILWAY CORRIDOR

It can be stated that various measuring techniques exist for monitoring of the railway corridor at European railway networks that are compliant with the state-of-the-art. Regarding the monitoring of the gauge is necessary to ensure the free space on the track required for ordinary traffic as well as for special transports and approvals of new rolling stock. One measuring system that measures solid objects (station platforms, signals, tunnels, bridges *etc*) within this corridor space is presented in the chapter. In this respect, it is also discussed that there are various measurement systems to acquire data. This includes stationary systems with stereo photography or stationary systems with laser detection.

A topic that has gained more interest in later years is trespassers and larger animals on the track. In contrast to the occurrence of solid objects, the situation may here change rapidly. Demands and potentials for monitoring are presented in the chapter.

13.4 MONITORING OF TRACK

This chapter has a similar outline as chapter 7 on vehicle monitoring. It is divided into key areas of monitoring that are presented in separate sections. Key parameters that relate to a safe, reliable, cost-efficient and environmentally friendly operations are outlined. How these parameters can be employed to describe the current status and how they relate to what is monitored today and what is possible to monitor is then discussed.

As for vehicle monitoring there is a wide range between parameters that are (at least in principle) very easy to directly assess to parameters that are close to impossible to evaluate directly (e.g. support conditions along a sleeper). In the former case, the challenge is to identify efficient and reliable methods to do the monitoring / inspection. In the latter case the major challenge is to deduce the sought information from indirect measurements.

As for chapter 7, the aim of the chapter is to provide a solid foundation to build from when current monitoring strategies are to be enhanced (as will be made in deliverable D4.1.3) – the chapter provides both suitable aims and potential challenges for such an enhancement. This information is crucial if a cost–benefit analysis should be carried out in relation to potential upgrading of monitoring capabilities.

13.5 MONITORING STATUS OF SUPPORT AND STRUCTURES

The chapter outlines key parameters, suitable status indicators and how measurements can be employed to estimate key parameters. This is done for bridges and tunnels. For each of these the presentation is divided into key areas. In particular current available monitoring technologies are presented. This provides a good basis for an infrastructure manager that seeks to improve monitoring capabilities by employing (and possibly adapting) off-the-shelf equipment.

13.6 MONITORING STATUS OF THE SIGNALLING SYSTEM

This chapter sets off from a short summary of state-of-the-art in signalling. In particular an overview is given on the ERTMS/ETC system and the different levels of this system. The chapter then focuses on monitoring systems – both track side and vehicle based – that can be used to ensure the function of the signalling system. Here some specific topics are discussed, balises, level crossing clearance, radio integrity. The chapter provides overview of objectives, current and potential techniques, challenges and possibilities with signalling monitoring. It also includes an example of operational equipment.

13.7 MONITORING OF OVERHEAD CONTACT LINE SYSTEM

The chapter focuses mainly on the pantograph/catenary interaction, which is one of the most critical railway interfaces. The chapter features a brief classification of the pantograph, catenary, and power supply systems. Different on-board and trackside monitoring systems currently exist and are described in the chapter – in particular a section is devoted to describe an existing monitoring system in detail. It further discusses how provided diagnostic information (e.g. parameters, aspects, *etc*) can be used in order to support design and development of new models and methods to be able to provide status characteristics and predict the evolution of functional degradation for maintenance purposes.

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