Deliverable D4.3
Development of technology for track and ride quality
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Executive Summary

The deliverable D4.3 represents the first steps in the development of technology for track and ride quality monitoring. First a review on the most used current technologies is presented. Then, the axle box acceleration (ABA) system is presented and analysed in the direction to its implementation in the study lines of the NeTIRail-INFRA project. Feasibility and preliminary studies were conducted in Romania and Turkey. It also includes the principles of the measurement systems used in the Slovenian railways. Then, preliminary results in The Netherlands are presented and discussed. Finally, some conclusion and steps towards the measurement in Romania and Turkey are given, with the expected results.
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### Abbreviations and acronyms

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<th>Abbreviation / Acronym</th>
<th>Description</th>
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<tbody>
<tr>
<td>EU</td>
<td>European Union</td>
</tr>
<tr>
<td>IM</td>
<td>Infrastructure Manager</td>
</tr>
<tr>
<td>LCC</td>
<td>Life-Cycle Costing / Life-Cycle Cost</td>
</tr>
<tr>
<td>MRT</td>
<td>Mean Repair Time</td>
</tr>
<tr>
<td>MTTF</td>
<td>Mean Time To Failure</td>
</tr>
<tr>
<td>RAMS</td>
<td>Reliability, Availability, Maintainability and Safety</td>
</tr>
<tr>
<td>UIC</td>
<td>Union Internationale des Chemins der Fer (International Union of Railways)</td>
</tr>
<tr>
<td>CM</td>
<td>Corrective Maintenance</td>
</tr>
<tr>
<td>IM’s</td>
<td>Infrastructure Managers</td>
</tr>
<tr>
<td>MGT/MGTPA</td>
<td>A measure of traffic in units of million gross tonnes per annum</td>
</tr>
<tr>
<td>PM</td>
<td>Preventive Maintenance</td>
</tr>
<tr>
<td>RCF</td>
<td>Rolling Contact Fatigue</td>
</tr>
<tr>
<td>US/UT</td>
<td>Ultra-Sonic / Ultra Sonic Testing</td>
</tr>
<tr>
<td>S&amp;C</td>
<td>Switches &amp; crossings</td>
</tr>
<tr>
<td>SZ</td>
<td>Slovenske Železnice – Slovenian Railway Authority</td>
</tr>
<tr>
<td>TCDD</td>
<td>Türkiye Cumhuriyeti Devlet Demiryolları – Turkish IM</td>
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<td>Delft University of Technology</td>
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1 General aspects of track and ride quality monitoring

1.1 Importance

Track and ride quality are no luxury but an economic necessity. Quality can be ensured by means of an optimal renewal plan and timely maintenance activities (1). In order to optimally reform renewal or maintenance plans, Infrastructure Managers (IM's) face decision problems that are intrinsically multi-objective. On the one hand, the track and rolling material should be in stable conditions, with acceptably slow degradation rates that guarantee a good service, minimum of traffic delays, and maximizing the infrastructure availability. On the other hand, budgetary constraints should also be considered to guarantee economic feasibility of the whole railways operation. In the railway business, it is well known that even though the service life of track is quite long (20 to 40 years), a period of inadequate maintenance will always show in a relative long period after, when the track evidently does no longer behave properly. The track and all the railway assets have memory, so short-term savings in terms of renewal or maintenance operation will severely affect the life cycle costs (LCC); and at the end, increase the total costs.

Reliability, Availability, Maintainability and Safety (RAMS) analysis, together with an effective corrective maintenance (CM) and preventive maintenance (PM), will help in keeping the quality as good as possible. Among the most important long-term costs we can mention the cost of renewal, cost of planned maintenance, cost of additional small maintenance, and cost of operational interference by both track work and due to inadequate quality. Thus, to keep LCC reduced, a good knowledge of not only the mean repair time (MRT) and mean time to failure (MTTF) of the assets is needed, but also their possible variations, as many sources of stochasticity can deviate the average behaviour of railway assets. Track behaviour depends on many factors, just to mention some of them: initial quality, state of the ground and formation condition (good drainage for instance), ballast quality, frequency of switches, traffic loading, type of track construction, curvature, type and quality of rolling stock among many other factors. In order to optimize the whole life costs (infrastructure and vehicles), effective tamping and ballast cleaning, rail grinding and renewal, sleeper and fastening renewal, investment on track-friendly traction units, will all reduce LCC (2). The costs of improving the track and ride quality will arise immediately in the short-term, but benefits will emerge in the long term, (1).

As a widely distributed ground infrastructure, railway infrastructures contain various and massive sensors and actuators to provide information for its structural health monitoring and maintenance. The sensors and actuators operate in real-time or periodically depending on their functions in different components. Vibration, ultrasonic, and eddy current measurements, together with video/pictures are common sources of information from railways and civil engineering structures in general (3), (4), (5), (6). They can easily become several terabytes of data and their relation within a predictive maintenance decision making is an open challenge (7), (8), (9), (10).
In this work package, among all the components, the focus is on the detection of rail surface defects. Suggested papers about track quality monitoring systems are (11), (12), (13). Next a brief description of the rail defects that will be investigated within the NeTIRail-INFRA project is presented.

1.2 Rail defects

1.2.1 Squats

Squat is a type of rolling contact fatigue (RCF). Squat has been known in Europe since about 30 years ago. The term originally comes from a resemblance to a heavy gnome which squatted on the rail. Squats appear on the running band in straight track and large curves, as are independent to the type of track. The origins of squats are diverse. Some of them could be due to corrugation, bad quality welds, and small indentations.

Figure 1-1 presents a reference photograph of a squat. The growth of squats depends on the dynamic contact between wheels and rails. Three classes of squats are defined: light (squat A), moderate (squat B), and severe (squat C).

![Figure 1-1 Squat](image)

Depending on the squat length $L_i(k)$, measured in mm, the severity of the squat can be used to represent the health condition of the rail at location $x_i$ as follows (14):

$$H_i(k) = \begin{cases} 
S & \text{if } 0 \leq L_i(k) < 8 \\
A & \text{if } 8 \leq L_i(k) < 30 \\
B & \text{if } 30 \leq L_i(k) < 50 \\
C & \text{if } 50 \leq L_i(k) < 60 \\
RC & \text{if } L_i(k) \geq 60 
\end{cases}$$
where S refers to a seed squat, A is a light squat (A squat), B is a moderate squat (B squat), C is a severe squat (C squat) and RC is a squat with risk of derailment. The boundaries were defined based on general guidelines to classify squats. To systematically classify squats in terms of severity, it should follow the terminology used in (15), (16) and (17). The definitions of these three references are compatible to one another. Although the transition between one class to another is not always abrupt, the defined fixed values for those transitions are according to our experience in the Dutch network.

The most important variable of a squat is the length, as it is related to the duration of the impact and to the wavelength characteristic (and therefore frequency) of the subsequent dynamic contact force, which is determined, by the Eigen characteristics of the track. Width is less relevant than length as it is mainly related to the severity of the defect and its growth is non-linear. For light squats caused by, e.g. indentations, the shape is usually irregular, depending on the shape of the objects causing the indentation. With the growth of the squats, the width becomes comparable to the length. But the length can grow further while the width is limited by the width of the rail (around 71mm). Depths are not considered because for light squats arising from indentations they are usually deeper than the compression of the contact bodies so that the bottom of light squats does not make contact with the wheel (the bottom is rusty and black). When the bottom does have contact with the wheel there are usually already cracks beneath the rail surface, indicated again by the rusty part. Thus, in the latter case the measurement of depth will also not provide good information because there is a kind of spring up effect coming from the crack that creates a gap between the cracked surface material and the bulk material underneath, which cannot be captured by geometry measurement under unloaded conditions. Next, in Figure 1-2 some examples of the geometry measurement made by a dedicated device called Railprof.

![Figure 1-2 Railprof measurements](image)

It is recommended to record videos/photos of the squat defects and to estimate their size, as in Figure 1-3. After consecutive measurement, it is possible to follow the dynamic of the defects. This information opens the possibilities to better adapt the maintenance strategies, anticipating the failures rather than reacting on them. In Figure 1-3, moderate and severe squats can be recognized by the following characteristics: localized depression of the contact surface of the rail head with a dark.
spot; widening of the running band; a shape of two lungs and cracks which start to develop Figure 1-3b) or are mature (Figure 1-3c). The light stage squats may not bear some of these characteristics, but the light squats can be recognized by a dark spot on the surface (Figure 1-3a).

Figure 1-3 Representative defects (a) Light squat, (b) Moderate squat, (c) Severe squat. Source: (18)

1.2.2 Corrugation

Rail corrugation is a periodic wave-like rail surface defect. The corrugation is up to date explained by a damage mechanism and a wavelength-fixing mechanism (19). According to the so-called mechanisms, corrugation can be classified into six types: short pitch corrugation (Figure 1-4a), rutting (Figure 1-4b), other P2 resonance (Figure 1-4c), heavy haul (Figure 1-4d), light rail, and track form related corrugation (Figure 1-4e). Among them the development mechanisms of short pitch corrugation are still unknown. Short pitch corrugation (subsequently shortened as “the corrugation”) refers to the corrugation with wavelength falling in the range of 20 – 80 mm, and with amplitudes (peak-to-trough distance) up to 100 µm. In the Dutch railway network, the most commonly recorded corrugation has the wavelength of 20 – 40 mm (20) (21). It mainly forms on straight tracks or at smooth curves under comparably light axle loads. It appears in different tracks, from traditional ballast tracks to modern slab tracks, from heavy rail to light rail and rapid transit, e.g. metro or tram lines, from discretely supported tracks to continuously embedded tracks (22). On one hand, the corrugation increases the vibrations/dynamical interaction forces of the vehicle-track system, thus accelerates the degradation process of key system components. On the other hand, the “roaring” noise due to the corrugation is a nuisance to residents nearby, especially in some densely inhabited areas.

Besides, corrugation can result in rolling contact fatigue, e.g. rail squats (3). So far, there is no complete explanation for the corrugation phenomena. Questions still open are:

- How the corrugation initiates and grows?
- How its wavelength changes?
- Why the corrugation only develops at some locations while not at others?
- What is the inherent connection between the corrugation and vehicle-track system parameters?

Therefore, it is necessary on one hand to further investigate the development mechanisms of the corrugation, and keep it under control by optimizing certain vehicle-track system parameters, and on
the other hand to remove the corrugation by means of grinding maintenance. Grinding increases the maintenance cost and reduces the network efficiency. From the IM’s concern, a robust, efficient and economical inspection system, which records the damage status of the track, is necessary to help them optimize their maintenance interval and related grinding parameters and quality evaluations.

Figure 1-4 Corrugation: (a) Short pitch corrugation in Dutch railway network. (b) Rutting, Source: (19). (c) P2 resonance corrugation, Source: (19). (d) Heavy haul corrugation, Source: (19). (e) Corrugation from resonance of baseplate of rail pad, Source: (19).

1.3 Measurement methods
The variety and amount of sensing information from the railway infrastructure constitute a complex network of data, from where the crucial information must be extracted to facilitate a good maintenance decision making. Considering the scale of, for instance, the railway infrastructure, the data fully conforms to the 5Vs characteristic of Big Data that are volume, velocity, variety, veracity and value (23) (24). In addition, a new V for Vulnerability should be considered, meaning that for most of the monitoring systems, the security level of the data is very important. Most of the railway data is not publicly available or shared, as vulnerability of the infrastructure and the business strategy of the contractors are important factors. Among all the V’s of Big Data, variety is one of the most difficult. With all the information extracted from the data, infrastructure managers can monitor the structural health of their assets and make maintenance decisions in a systematically way. The configuration and integration of sensors for structural health monitoring must be implemented in a way that ensures that good and sufficient data can be provided while having minimum impact or interventions on the infrastructure. The design and selection of sensors are determined by the methodologies that will be adopted for information extraction and decision making. In Table 1.1 – a summary of rail monitoring methods are discussed in (25).

The purpose of ultrasonic measurement is to check the rails for internal defects. The inspection is done by rail vehicles but can also be done by using hand equipment. It can measure depths from 4mm. The speed of an ultrasonic train varies. In the Dutch HSL, the UST96 train is used and it runs up to 40 km/h. The UST96 train uses two probe blocks for each rail which contains two 0°, two 70°, two 35° and two additional 70° transducers for inspection of the inner side of the rail head (26). The trains carry about 6000 litres of water because water is used as a contact fluid for the measurements. The purpose of the Eddy current measurement method is to detect and evaluate defects close to the surface. The inspection can be done by either rail vehicles or by hand measurement using for instance the Sperry EC walking sticks. It can measure crack depths from 0.3mm to 5mm. As usually the gauge corner of the rails is monitored by eddy current; however, severe damages can also occur on the rail head. So it is recommendable to measure the complete profile.

There are also other measurements, such as the rail profile to check whether an adequate wear reserve is available. Measurement of the rail profile can be done manually, measuring with the Miniprof or with the use of a profile mould. The measurement can also be done automatically by using rail measurement vehicles (e.g. the measurement train of Eurailscout or NMBS). Systems installed on most of the rail measurement vehicles, are the so-called optical measuring systems. These are non-contact optical systems for inertia-free scanning of the rail running edges and the rail head profile. Rail roughness measurement is to calculate the average rail roughness level and to check whether it fulfils the acoustic equivalence. Rail roughness can be measured directly with a hand-held micro-displacement measurement device (e.g. with the RM 1200 E) or indirectly through sound or vibration measurements on train wheels. In this work package, the focus is on detection of rail surface defects with the use of axle box acceleration (ABA) technology. While all the measurement systems have their advantages and disadvantages, we believe that the correct “information fusion” coming from all the measurement systems can enhance the knowledge of the real condition of the track and enhance the quality of the maintenance decisions.
### Visual inspection
- Human eye
- Large damages visible on the surface
  - A trained eye can judge the damages immediately also in relation to the context, location, history
  - A trained inspector can also evaluate not only surface rail defects, but also the whole profile and the track
- Crack depth is unknown
- Need of artificial light when inspections are in the night
- Prone to human error

### Camera inspection
- Capture by an on-board camera. Processed later by the inspection department
- Visible damages on the surface
  - High speed cameras are nowadays easily available, so it is possible to cover in relative short time large extends of tracks
  - Image processing techniques are available, it is possible to automatize the detection
- Crack depth is unknown
- Need of the correct artificial light
- Contaminations tend to trigger false defect detection
- Small and invisible defects cannot be detected

### Ultrasonic measurement
- Ultrasonic energy
  - Cracks larger than 4mm under the surface
- Current technology can measure large parts of the track during one shift
  - Both available for hand measurements (for special structures) and complete track measurements
  - Can also measure the web and the part of the foot straight under the web of the rail profile
- Cannot measure defects less than 4mm
  - Defect hit-rate is quite low. The US measurement is preferred as a global indicator of the quality
  - Cannot measure the direction of the crack

### Eddy current measurement
- Electrical current, magnetic fields
  - Cracks up to 5mm of depth
- Can measure early defects from 0,3mm up to 5mm of depth
  - Walking sticks and other equipment of Sperry are available for detailed measurements
  - Walking sticks are very labour intensive to measure large tracks
  - Cannot measure the direction of the crack

### Rail profile measurement
- Contactless measurement by laser
  - Wear of rail surface from 0,2 mm
- Up to 80 km/h measurement speed
- Rail profile measurement

### Surface corrugation measurement
- Inductive sensor
  - 30-100 mm and 100-300 mm rail surface corrugation
- Can measure smaller rail corrugation in comparison to the acceleration measurement
- Can measure only up to 300 mm wave length

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**Table 1.1 – Short summary of rail surface defects monitoring methods. Most of them are used in the case study lines of the NetIRail-INFRA project. Modified version from Source: (25).**
2 Axle-box acceleration measurement system for track quality

In the Dutch railways, the vertical axle box acceleration (ABA) was employed to detect defects such as severe corrugation and poor quality welds. In other countries like Korea (27), Japan (28), Poland (29), Italy (30), ABA systems have also been implemented for analysis of railway track defects. To have a better understanding of the state of the art regarding the use of ABA to monitor Railway infrastructure, in Table 2.1 a summary of past research is included. In the references (18) and (21), the use of the ABA measurement system was presented for the detection of squats on a large set of data in The Netherlands, eight measurement rounds each year from 2009 to 2011, each measurement round included three repetitive measurements on two sections of track of 3 km long.

<table>
<thead>
<tr>
<th>Ref.</th>
<th>ABA implementation</th>
<th>Defects studied</th>
<th>Frequency range</th>
<th>Railway network</th>
</tr>
</thead>
<tbody>
<tr>
<td>(29)</td>
<td>Vertical ABA, 2 sensors, 80km/h</td>
<td>Corrugation, wavelengths 0.055 – 0.080 m</td>
<td>Measured up to 2864Hz</td>
<td>Polish State Railways Network</td>
</tr>
<tr>
<td>(30)</td>
<td>Vertical and Lateral ABA</td>
<td>Corrugation, Lateral discontinuity, curve rail wear, damaged switches</td>
<td>Measured 1000-7000Hz, Analysis between 25Hz-1246Hz</td>
<td>Subway of Milan, Italy</td>
</tr>
<tr>
<td>(32)</td>
<td>Vertical ABA Lateral ABA</td>
<td>Alignment, zones of large lateral force, track irregularities below 100Hz</td>
<td>Analysis up to 100Hz</td>
<td>Japanese high speed railways</td>
</tr>
<tr>
<td>(27)</td>
<td>Vertical ABA Lateral ABA at speed 300km/h</td>
<td>Long wavelengths irregularities, from 3m to 200m both lateral and vertical irregularities</td>
<td>Analysis up to 2048Hz</td>
<td>Korean Train Express, high speed line</td>
</tr>
<tr>
<td>(18)</td>
<td>Vertical ABA Longitudinal ABA at speed 140km/h</td>
<td>Squats</td>
<td>Analysis up to 3000Hz</td>
<td>Dutch railways, conventional line</td>
</tr>
</tbody>
</table>

Table 2.1 – Reported implementations of ABA systems, as in (18)
2.1 Principles of the TUD axle box acceleration measurement

The system measures longitudinal and vertical ABA because the focus is on detection of short wave irregularities (see in the wheel and directions). Lateral ABA has been employed in the railway literature in the frequency range below 100Hz, applicable for longer wave track irregularities, out of the scope of this work package.

A vertical track irregularity like a squat causes an impact to a wheel in the vertical direction (y direction in Figure 2-1), which induces forced vibration of the wheelset. The vibrations caused by the impact are then transmitted from the wheel-rail interface to the axle. In the case of longitudinal and vertical acceleration (x and y directions in Figure 2-1), axial symmetry of the wheel permits to analyse some correlation between them and squats (plane x-y). In fact, in the interested region between 400Hz and 2000Hz we can observe a correspondence between many of the peaks and dips of both the vertical and longitudinal signals in Figure 2-2, meaning that there are many excited modes in common in the two directions. In Figure 2-2 is included three indications (arrows) to the three theoretically most prominent modes that it was possible to find in the measurement over the real wheel. This is the theoretical foundation for the use of longitudinal ABA to sense vertical impact to improve sensitivity.

Figure 2-1 – Wheel and directions, Source: (18).

Figure 2-2 – Inertance by hammer test on the wheel. Axially symmetrical modes correspond to prominent peaks indicated with an arrow, Source: (18).
The mode shapes of the wheelset can be classified into two groups: wheel modes and axle modes. According to (33) and (34) all the wheel modes are symmetric or anti-symmetric with respect to the axle. For this reason, squat-induced wheel vibration can be measured both in vertical and longitudinal directions on the axle box. As for the axle modes, according to (34), they are classified into 3 groups: flexural, torsional and compressional. Flexural modes will be excited by vertical impacts and have components in the x and y directions, while in the z direction this component will be small, if any. Torsional is non-symmetric with respect to the wheel and the axle and has no components in z direction. In the case of compressional modes, they are mainly in the lateral (z) direction. They have, however, no components in the longitudinal or vertical directions, so the chance for them to be excited by a vertical force is small. Therefore, in summary, the vibration modes excited by a vertical force will mostly be in the vertical (x-y) plane. From the above discussion, it becomes clear that lateral ABA is more sensitive to lateral excitation, thus to be excited by flange contact rather than by squats.

In the case of light squats/indentation, their length is typically 10 to 30 mm. For normal traffic speed of 140 km/h and for the speed of the measuring train (100 – 110 km/h), they cause frequency contents of 1.0 – 4 kHz for the forced vibration/impact part. In other words, light squats cause higher frequency vibrations because its effects on the signals are more like an “ideal” impact, which in its perfect form has zero time duration. In Figure 2-3 the effect of the signal processing procedure used when analysing the detection signal is shown (21). In Figure 2-3, the peaks of the scaled average wavelet power (SAWP) signals after processing are more intense and evident, which makes the detection procedure easier. The defects are denoted by red asterisks. The defect at 3.8 m is a moderate squat. The other defects are all trivial defects.

Figure 2-3 – SAWP before and after signal processing. Visible defects are shown with red asterisks on the horizontal axis. The detection of small defects is much easier with the new instrumentation and method.

Source: (21).

2.2 Equipment
In Figure 2-4, a schematic overview of the ABA system is shown. Data is collected from accelerometers, a GPS receiver and either a tacho or speed-sensor for positioning.

![Figure 2-4 - Principle of the ABA measurement system](image)

For ABA measurements, a number of accelerometers are mounted on the axle boxes of at least one bogie. For mounting the sensors, three small mounting studs have to be glued on each axle box. Therefore, a small spot of approximately 2x2 cm should be cleaned and be free of paint and grease, see Figure 2-5.

Sensor cables are routed from the bogie frame to the measurement box in the train, preferably through a cable entry. If a cable entry is not available, the cables can be routed through an open window. As it is for temporary use, the cables are attached by cable ties so they can easily be removed after the measurements. The mounting studs are not removed after the measurements.

Installation of the sensors and cabling (including gluing the studs) can be carried out in one full day. It is strongly recommended to have the train placed indoor, as the axle boxes should be protected from rain during the gluing process. For safety reasons, it is also recommended to have the train in a workshop in order to mount the GPS antenna on the roof of the train (strong magnets are used to hold the antenna). The measurement box (see Figure 2-6) contains the data acquisition. The box requires a 230V /50Hz power supply.
GPS data is obtained from a GPS receiver that will be placed in the measurement box. The GPS antenna is placed on the roof of the train and mounted via a baseplate containing a strong magnet. Thus, the roof of the train must be ferromagnetic. The GPS antenna cable is routed through an open window or,
if available through a cable entry to the measurement box. For accurate positioning measurements, either a tacho signal or a speed signal should be provided from the measurement trains electrical installation.

During measurements, an operator should be in the train to control the ABA measurement system and to check for error and warning signals from the ABA system. Trailing bogies are preferred for mounting the accelerometers. It is important to notify of possible grinding operations, in the period before the measurement and until the validation. In case grinding is performed, there will be no light defects to detect and/or verify.

The response related to the wheel defects can be excluded from the vertical signals by either filtering ABA signal in the frequency domain by a stop-band filter or by subtracting the specific repetitive pattern from ABA in the time domain. This procedure does not affect the detection of rail defects, as far as the frequencies related to squats are in different frequency bands than the ones related to wheel defects. We recommend to avoid the use of damaged wheels in the ABA measurement, so as to get a better signal.

The ABA signal is greatly influenced by the train speed. The measurement train used so far has a nearly constant speed of 100 km/h in the interesting locations. We recommend to measure at the commercial speed, with the lowest number of stops if possible. When the train speed varies, quantitative relationships with the signature tunes and maximum ABA can be incorporated using a regression model, to make full use of the data collected.
3  Feasibility study for the NeTIRail-INFRA case study lines and data collecting activities

3.1 Feasibility requirements and planning

For the case study lines of the NeTIRail-INFRA project, TUD has arranged pre-visits to the train that are intended for the measurement. The purpose of the pre-visit is to decide on the details of the instrumentation so that there is sufficient time to order all the necessary materials on time.

For the measurement itself, with one trailing bogie to mount the sensors for measurement, at least two runs of the measurement train on the same track section in the same travelling direction with approximately the same speed are required. If it is difficult to have all the runs on one day, they can be done within 5 days. The main goal of the measurement is to detect squats, though many other rail defects like corrugation, poor welds, and poor insulation joints are expected to be detectable.

It is also important to arrange the following extra measurements in the measured track section(s), to verify the detection:

1. Visual inspection with photography.
2. Hammer tests.
3. Railprof measurement.
5. Other track measurements if available.

The track visit/measurement can be done before, during and/or after the ABA measurement. An efficient measurement campaign could be:

Day 0: Installation of the ABA sensors (maximum 2 consecutive days).
Day 1: ABA Measurement (one-two runs over the same track kilometres).
Day 2: Processing of the signals, and track measurements in interesting kilometres.
Day 3: Track visit for validation. Installation of the sensors for ABA.
Day 4: ABA Measurement (one-two runs over the same track).
Day 5: Track visit for last validation and track measurements.

To analyse the feasibility of the ABA measurement, the partners have to send the following information:

1) Technical drawings of the axle box. If not available, pictures of the axle box. Detailed information of the axle boxes of the trailing bogie that can be used is critically important for designing the instrumentation. If no more detailed drawing is available, it is highly appreciated if clear photos of the axle boxes are available from all view angles – sides, ends, top and bottom views, etc. Particularly, the pictures of the axle box from beneath and from all the sides are crucial.
2) Description of the train that can be available. Is it possible to install the accelerometers in a not motorized wagon?

3) Type of braking system: Disk braking or track braking? The best for the measurement are disk braking.

4) Is power available in the train? Some equipment/PC/sensors are needed on-board and require power. If not available, is it possible to use a generator on-board?

5) Can a tacho signal from the train be made available? The signal is needed together with the GPS to improve positioning. Is GPS available in the train?

6) Is it allowed that we put cables through the windows of the train?

To facilitate the best decision, all the information about the track section(s) that are going to be measured are needed to be available:

1. High speed or conventional.
2. Passenger, freight or mixed.
3. Ballasted or ballast-less.
4. Concrete or timber sleepers.
5. Speed limits.
6. MGT per year.
7. Other available information, track geometry, dynamic measurements from previous years, track characteristics.

3.2 Analysis Romania

The SNCF Class X 4500 that operates on the line Bartolomeu - Zarnesti can be employed (see Figure 3-1). Additional information about X 4500 trains:

1. Available power source 72 VDC.
2. Tacho signal available on train and also GPS positioning.
3. For test purposes, we can find solution for cabling.

Info about the case-study line (see Figure 3-2):

1. Line speed 80 km/h.
2. Mixed line (passengers and freight).
4. Concrete and timber sleepers.
5. MGT/year = 10.
In July 2016, a pre-visit was conducted. In Figure 3-3, some photos under the train of measurement are presented, where the sensors will be mounted in the axle box during the measurement. Figure 3-4 shows some examples of RCF defects that were found during the track inspection. It is expected that the ABA measurement can detect those defects. Figure 3-5 shows some insulated joints in the case line. Although insulated joints are not one goal of the NeTIRail-INFRA project, it is possible to deliver some rough indications of their condition based on (35), (36), (37). Figure 3-6 shows some of the railway asset that are not going to be analysed: switches, bridges, fastening systems and sleepers.

After the feasibility analysis, a first measurement trial was planned in the end of September 2016. The analysis of the measurement will be explained in the final deliverable D4.4.
Figure 3-3 Photos of the axle box.

Figure 3-4 Photos rail surface defects in Romania.
Figure 3-5 Photos insulated joints in Romania.

Figure 3-6 Photos of switch, fastener, bridge and sleepers in Romania.
3.3 Analysis Turkey

For the measurement in Turkey, the TCDD Roger 800 - Road and Catenary Measurement Machine is available. It is a specialized measurement train, with the following systems incorporated:

- Train localization system.
- Track geometry measurement system.
- Rail profile measurement system.
- Rail corrugation measurement system.
- Track surface inspection and measurement system.
- Fishplate inspection system.
- Overhead line measurement systems.
- Catenary-pantograph interaction and overhead line dynamic geometry measurement system.
- Acceleration measurement system.
- Overhead line defects detection system.
- Gauge measurement system.
- Track video surveillance system.
- On-board database system.
- Train data and synchronism network.

A drawing and pictures of the Roger 800 are given in Figure 3-7.
From the feasibility analysis, it was concluded that a pre-visit could be performed in Turkey. From the 4th to the 6th of April 2016, a delegation of the TUD visited the railway track near Ankara, Turkey, to perform the pre-visit necessary to evaluate the possibility of measuring with the axle box acceleration technology the health condition of the railway track. Jan Moraal and Jurjen Hendriks (TUD) were received by Elif H. Öztürk and Ali Salih Akbaykal from the Intermodal Transportation & Logistics Research Association (INTADER) of Turkey. Different meetings were conducted and track-train visits were all organized by INTADER and TCDD, see Figure 3-8.

Originally, the track section that was planned to be measured starts in Kayas and ends in Lalahan. Recent renewal of the track will modify the case study of the measurement, although the Roger 800 and the team remains the same.

![Figure 3-8](a) Having a meeting in the Roger 800: Jan Moraal, Yavuz Bozoklu, Elif H. Öztürk, Ali Salih Akbaykal, Barbaros Kucukakin, Yusuf Suvag. (b) The Roger 800 from the outside. (c) Double track segment of the track that starts in Kayas. (d) A track that ends in Lalahan.
Figure 3-9 Some rolling contact fatigue examples that were found during the track visit, (a) squat, (b) short pitch corrugation, (c) insulated joint with damaged insulation layer, (d) weld, (e) surface damage, (f) damaged weld.
3.4 Analysis Slovenia

Monitoring of the condition of track on Slovenian railway network is carried out with multiple measurement technologies and different methods and measuring equipment. For diagnostics of railway tracks or rails the following measurements among others with measuring trains are carried out:

- Rail profile (rail head wear).
- Corrugation (rail surface corrugation).
- Head check (rail defects).
- Ultrasonic (US) inspection (US inspection of rail defects).

Faults on rails, detected by means of acceleration measurement with low and high frequency sensors can be compared with existing data measured with the diagnostic measuring methods used on Slovenian rail lines. For each case study line, SZ has existing data of track wear and ultrasound and for rail line Divača-Koper (main line) also corrugation and head check data.

Beside the measuring trains for monitoring of faults of tracks, SZ uses the technology of acceleration measuring with equipment mounted on passenger vehicle (EMG 310), it could be installed also on any other vehicle. For the purpose of measuring of dynamic parameters, SZ measures the vertical and lateral accelerations on the undercarriage of the train. This technology could also be used for the purpose of fault detection on the tracks or rails:

- Low frequency accelerometers (sensors): intended primarily for the measurement of dynamic parameters, vertical and horizontal (lateral) acceleration on the bogie;
- High frequency accelerometers (sensors): intended to detect faults on rails based on measurements of vertical and horizontal accelerations in the axial pairs of wheels of the bogie.

3.4.1 Technology of measurements of dynamic parameters

Measurements of dynamic parameters are implemented in Slovenia with an electric train type 310 with integrated tilting (EMG 310) and measuring equipment ENSCO and Dewesoft on driving routes of fast tilting trains (Pendolino). For this purpose, the equipment is installed on the bogie, in the cabin and on the roof of train composition. Installation is carried out in the workshop.

SZ measures the vertical and horizontal accelerations on the bogie of the vehicle and in the cabin (passenger comfort), the location of measurement and vehicle speed. The results of the measurements are mainly evaluated during the driving of the composition to the starting position.

After completing the measurements of tracks, the dismantling of all measuring devices (undercarriage, cab, roof) is performed and a review of the composition. Measurement data processing and preparation of the report follow after completing the measurements and dismantling of the equipment. For the purpose of the project, NeTIRail-INFRA, the measurements are carried out on
passenger trains on three line categories: busy capacity limited passenger railway, under-utilised rural or secondary line, and a freight dominated route.

**Calculation and measurement of path**

When calculating the length of the path and the position of the train, the following baselines are considered:

- Train: train type, length and gross weight of the train.
- Traffic conditions: train stops at stations.
- Rail line sections with mileage (longitudinal position) of stations.
- Measurement of time.
- GPS speed measurement.
- GPS measuring and plotting the position.
- Calculation of the path.
- Calculating the corrected path with relevant mileage.

**Purpose of the measurement of the dynamic characteristics of lines**

Measurements of dynamic characteristics of the rail line are conducted in order to determine the maximum operating conditions considered to the restrictions, based on the structural properties of the track and the influence of track on the dynamic behaviour of the vehicle, taking into account safety, mechanical fatigue of track and driving characteristics.

The railway line as the object itself has no dynamical characteristics, but its geometric characteristics, materials and the environment significantly affect the dynamic behaviour of the vehicle. The dynamic behaviour of the vehicle depends on the type of vehicle on the track, but because of the close correlation with the characteristics of the track it is often appointed as the dynamic characteristics of the track.

**Measuring equipment**

Dynamic measurements on the ICS train are performed with the measuring equipment for measuring the acceleration and position of the train. The manufacturers of the measuring equipment are Dewetron, Bruel & Kjaer, Ensco, Leica, Trimble and ICS. The software is Dewesoft adapted for the measurement of dynamic parameters of railway lines.

On the roof of the train there are two GPS antennas (Leica and Trimble) which are necessary to determine the location of the measurement and to accurately determine the speed of the composition. Accelerometers are mounted in the first bogie. All this equipment is linked to the central unit in the vehicle.

**Measured parameters**

In accordance with the functionality of the measuring equipment the measurements of various dynamic parameters are performed. We measure location, speed, acceleration and vibration in the lateral and vertical direction on the axis of the bogie. Inside the cabin we measure vertical and
horizontal acceleration - passenger comfort. Measurements of the dynamic parameters and the speed are carried out with a frequency of 4000 Hz and in the calculations averaged with a frequency of 10 Hz, which means 10 values of the data in one seconds.

In assessing the dynamic characteristics of the rail line for train with tilting in accordance with EN 14363:2005, the conditions for conventional vehicles are applicable, more specifically, "passenger vehicles with two-axle bogies: V ≤ 200 km / h: measurement of acceleration on the basket and the bogies of the vehicle". The vehicle is tested empty and with a normal load of passengers. The track should be dry during the test run. In any case, atmospheric conditions are recorded during the test. During the test run, all data are recorded on electronic memory media. Values that are used for real-time analysis - mainly due to the safety conditions are displayed graphically. Prescribed bandwidth filters are used for real-time graphical presentation.

The processing of variables for the evaluation

Processing of variables is done automatically on the basis of recorded data. The sampling frequency is 200 Hz. The aim of processing is to score maximum values.

Accelerations of the bogie give information about safety, while acceleration in the basket of the vehicle talks about the driving characteristics and comfort. For data processing we perform a simplified method by calculations on the measured acceleration.

The results of the measurements are processed according to the measured rail line sections. In addition to the measured speed and the path of the vehicle the minimum and maximum measured values of dynamic parameters are shown - the average lateral acceleration, lateral forces and derailment coefficient.

Figure 3-10 Accelerometers on the bogie of a passenger train, left side
3.4.2 Technology of measurements with high frequency sensors

Measurements are carried out by using a measuring system DEWE-2500 with IEPE inputs installed to enable direct connection of accelerometers. The software package Dewesoft enables capture of the raw signals and the calculated or converted values of the acceleration (speed of vibrations or movements - depending on what is the output signal needed for analysis). The program Dewesoft enables to show signals on different displays and export data to other software packages for further analysis.

The measuring system allows capturing signals with a total sampling rate of 250 kHz. In view of the interesting frequency range (400 to 2000 Hz) a reasonable selection of sampling rate is of > 20 kHz (25.6 kHz or higher frequency). We use the GPS sensor with 1 Hz refresh to measure the speed and position and 2 or 3 IEPE accelerometer with a measuring range of +/- 50 g (acceleration due to gravity). Frequency range of accelerometer would be between 1 Hz and at least 6000 Hz.

Measured parameters are as follows:

- Vibration (acceleration).
- Speed of vibration.
- Speed.
- Position or any other sensors (camera for video recording).

Output measured data are:

- Vibrations or accelerations (m / s² or g).
- Speed (km / h or other unit).
- Positioning coordinates.
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Figure 3-12 DEWE-2500 System

Figure 3-13 IEPE accelerometer inputs
4 ABA measurements in The Netherlands

4.1 Squat monitoring using ABA measurement technology

Among common measurement technologies of surface defects on the rail including eddy current testing, ultrasonic measurements, visual inspection, ABA measurements were employed (see Figure 4-1). The reason to use the ABA measurements is that for preventive maintenance, the measurement method needs to detect squats in an early stage. In this detection algorithm, the squat location and the severity are estimated by wavelet spectrum analysis and advanced signal processing methods. By adopting ABA energy signal and the understanding of vibration caused by the wheel-track behaviour, the severity level of the squat can be predicted. To employ the ABA signals to estimate the length of squats, a model is used to relate visual lengths correlated to the maximum power spectral density gained by the ABA signals. The obtained length measurements are used as an input for the prediction model to capture the stochasticity in growth within three different growth scenarios as explained in the next section (14).

Figure 4-1 Global scheme of the ABA measurement system, Sources (14), (38).
4.2 Squat growth modelling

Since the squat’s length grows over time when the squat gets severe, for assessment of the squats growth it is necessary to estimate the squats length at various time instants. Therefore, this section presents the model for estimation of the length of squats by ABA measurements. Some frequency components of the ABA signal are related to the length of squats. Particularly, the power spectral density at 300 Hz increases with the growth of the squat’s length. In the real-life measurements, the frequency characteristics of ABA may vary at different locations. For this reason, the maximum power spectral density in the frequency band between 200 Hz and 400 Hz, denoted by $P$, was used for estimation of the length:

$$
P = \max_{200 \leq f \leq 400} \{PSD_{ABA}(f)\}
$$

The data obtained from the track Eindhoven – Weert used for the investigation of the relationship between the power spectral density and the length is in Table 4.1.

<table>
<thead>
<tr>
<th>Squat</th>
<th>Length, mm</th>
<th>ABA, m/s²</th>
<th>P</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>24</td>
<td>89.8</td>
<td>66.0</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>10.5</td>
<td>0.3</td>
</tr>
<tr>
<td>3</td>
<td>23</td>
<td>27.3</td>
<td>27.4</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>24.3</td>
<td>2.3</td>
</tr>
<tr>
<td>5</td>
<td>19</td>
<td>27.6</td>
<td>4.8</td>
</tr>
<tr>
<td>6</td>
<td>21</td>
<td>21.8</td>
<td>6.1</td>
</tr>
<tr>
<td>7</td>
<td>18</td>
<td>31.0</td>
<td>4.0</td>
</tr>
<tr>
<td>8</td>
<td>23</td>
<td>25.0</td>
<td>9.4</td>
</tr>
<tr>
<td>9</td>
<td>23</td>
<td>21.1</td>
<td>3.5</td>
</tr>
<tr>
<td>10</td>
<td>18</td>
<td>17.6</td>
<td>3.2</td>
</tr>
<tr>
<td>11</td>
<td>19</td>
<td>45.4</td>
<td>7.9</td>
</tr>
<tr>
<td>12</td>
<td>31</td>
<td>65.5</td>
<td>107.4</td>
</tr>
<tr>
<td>13</td>
<td>13</td>
<td>15.5</td>
<td>1.9</td>
</tr>
<tr>
<td>14</td>
<td>35</td>
<td>48.2</td>
<td>46.2</td>
</tr>
<tr>
<td>15</td>
<td>29</td>
<td>20.5</td>
<td>28.2</td>
</tr>
<tr>
<td>16</td>
<td>24</td>
<td>30.4</td>
<td>10.4</td>
</tr>
</tbody>
</table>

Table 4.1 – The field data squat for visual lengths measured by power spectrum density in frequency band around 300 Hz.
The data listed in Table 4.1 is presented in Figure 4-2. It can be seen from this plot that the relation between the squat’s length $L$ and the power spectral density $P$ is similar to a power function. Therefore, a model for estimating the length was constructed as follows:

$$L = 13.371P^{0.2012}$$

The coefficient of determination $R^2$, which is a measure of how well the model approximates the real data points, is 0.8 for this model.

![Graph showing the model for estimation of the length of squats. Variation over time of the length will indicate how fast squats are growing, which is part of the further research. Source: (39).](image)

**4.3 Design of key performance indicators (KPIs)**

Relying on the ABA measurements, number of squats can be used by a predictive tool to support the infrastructure manager’s decision on how to keep controlling the squat growth over time. Together with the squat numbers, significant density of B and C squats can represent a high potential risk to track safety. According to the squat detection and modelling tool, number of squats and density of B and C squats are used as key performance indicators (KPI’s).

A vector including all the KPIs called $y_{h,j}(t)$ can be defined to cover the proposed KPI’s in terms of time step $t$, scenario $h$ and track partition $j$:

$$y_{h,j}(t) = \left[ y^1_{h,j}(t), y^2_{h,j}(t), y^3_{h,j}(t), y^4_{h,j}(t), y^5_{h,j}(t) \right]^T$$

where $y^1_{h,j}(t)$, $y^2_{h,j}(t)$, $y^3_{h,j}(t)$, $y^4_{h,j}(t)$ and $y^5_{h,j}(t)$ are the number of A squat, the number of B squat, the number of C squat, the number of RC squat and the density of B and C squats, respectively.
5  Remarks, future planning and conclusions

In this deliverable, first a brief description of track and ride quality monitoring systems was given. As the focus of this work package is the detection of rolling contact fatigue, the TUD ABA measurement system is explained. Feasibility and pre-visit results in Romania and Turkey are also reported. Finally some results obtained in a track in The Netherlands can be used as examples of how the measurement results can be eventually being used.

In the coming period, two measurements are being planned. By the end of September 2016, the track Bartolomeu - Zarnesti in Romania will be measured. The results will be reported in the final deliverable D4.4. During the first quarter of 2017, it is expected to measure in the case study line of Turkey.

Feasibility study was also done for the track in Slovenia. The measurement system used by SZ is fully described in this deliverable. In this case, the trains available for measurements do not belong to the partner of the project (SZ), making difficult the access to both tachometer and power. This, together with other technical difficulties, concluded in prioritizing the measurements in The Netherlands, Romania and Turkey.
6 Bibliography


