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Smart technology solutions for the NeTIRail-INFRA case study lines: Axle box acceleration and ultra-low cost smartphones

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Abstract

In this paper, we present preliminary results on the development of smart technology solutions for lower density railway lines. The goal is to reach a cost effective inspection and asset management to minimize maintenance interventions time/cost without dedicated inspection vehicles. The proposed methods include axle box acceleration measurements and ultra-low cost smartphones. The collected data will be further used to increase knowledge of the condition of the railway track and to estimate the comfort of passengers. In order to make use of the data, the data is interpreted and converted from monitoring information into management information. Feasibility and preliminary studies were conducted in the railway lines of Romania. The results presented in this paper were obtained in the framework of the H2020 project NeTIRail-INFRA, Work Package 4: Monitoring and Smart Technology.

Keywords: Railway technology; axle box acceleration measurements; ultra-low cost smartphones; railway track quality; train ride comfort; H2020 project.

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Nomenclature

NeTIRail-INFRA	Needs Tailored Interoperable Railway Infrastructure
ABA	Axle box acceleration
RCF	Rolling contact fatigue
LBS	Location-based services
ADS	ADS-Electronic Research SRL (Analogic & Digital Systems)

1. Introduction

Railway lines across Europe face multiple challenges. Some examples are to further increase of capacity, improve quality of services, shorten travel time, among many others. Particularly, in the case of regional underutilized lines, one of the greater challenges is to develop new technologies that maintain a reliable service based on a smart maintenance strategy, considering cost limitations, safety standards, and new concepts on sustainability and societal impact that go beyond the conventional economic analysis of highly utilized railway track.

A good track and ride quality are no luxury but an economic necessity, no matter what the railway line we are talking about. Quality can be assured by means of an optimal renewal plan and timely maintenance activities (Veit, 2007). To optimally determine renewal or maintenance plans, Infrastructure Managers face decision problems that are inherently stochastic. Track behavior 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. Additionally, degradation of the components is affected by multiple sources which are difficult to control and some are exogenous such as weather conditions. Also, every monitoring system of the infrastructure relies on sensors which are affected by different type of noise. As a widely distributed ground infrastructure, railway infrastructures are distributed parameter systems evolving over time and dependent on the different locations. Thus, decision making in railway infrastructure is a complex problem. Short-term savings in terms of renewal or maintenance operations may end up increasing the total costs as those savings may severely affect the life cycle costs of the infrastructure (Lichtberger, 2007).

Vibration, ultrasonic, and eddy current measurements, together with video/pictures are common sources of information from railways and civil engineering structures in general. They can easily become several terabytes of data and their relation within a predictive maintenance decision making is an open challenge. The H2020 project NeTIRail-INFRA develops new models and technologies that are tailored to the needs of different railway systems. In this paper, preliminary results on the development of smart technology solutions for lower density railway lines are presented: axle box acceleration (ABA) measurements and ultra-low cost smartphones.

1.1. Axle box acceleration (ABA)

A track irregularity like a squat or weld condition causes an impact to a wheel, 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, axial symmetry of the wheel permits users to analyze some correlation between them and the local irregularity (Li et al, 2015).

In the Dutch railways, ABA measurement has been used for the detection of rolling contact fatigue (RCF) (Li et al., 2011; Molodova et al. 2011; Molodova et al., 2014; Li et al., 2015), degradation monitoring of insulated rail joints (Oregui et al., 2015; Molodova et al., 2016), and for monitoring of railway crossings (Wei et al., 2017). In other countries like Korea (Lee et al., 2012), Japan (Sunaga et al., 1997), Poland (Massel, 1999), Italy (Bocciolone et al., 2007), ABA systems have also been implemented for analysis of railway track defects. The data is collected from accelerometers, a GPS receiver and either a tacho or speed-sensor for positioning. For the monitoring of the entire Romanian railway, the measurement would provide a data volume of several terabytes. The system can be implemented in passenger trains (on-the-run measurement), which reduces the cost in comparison with using specialized measuring trains. The implemented system measures longitudinal and vertical ABA because the focus is on detection of short wave irregularities. Lateral ABA is applicable for longer wave track irregularities, out of the scope of this research.

1.2. Ultra-low cost smartphones

Smartphones have powerful computing, communications, and sensing capabilities. In addition to the ability to perform complex computerized tasks and communicate wirelessly with other systems, they have a rich set of on-board sensors such as accelerometers, gyroscopes, GPSs, etc. Within the NeTIRail-INFRA project in Task 4.3, a prototype system dedicated to low cost smartphones was developed. Information on board the vehicles, vibrations, speed, GPS positions were collected in order to estimate ride comfort and to estimate track conditions.

For the actual implementation, the Android operating system was considered given that most smartphones run with it. Android platform is a smart mobile phone platform launched by Google. Android provides the support of mobile map and location based services (LBS). The most important aspect regarding the features of Android smartphone is that the phone's hardware functionality is not only limited to the manufacturer's interest, but also can be extended by the user. Therefore, external components such as sensors or other remotely sensed objects can be connected to the smartphone, maximizing the smartphone's hardware added value.

Android system supports three types of sensors:
1) The first type is motion sensors that measure the acceleration and rotation of a device, e.g., accelerometers and gyroscopes.
2) The second type is environmental sensors that give the information about the surrounding environment of a device, e.g., barometers, thermometers.
3) The third type is position sensors that provide positional information for a device, such as orientation. These include orientation sensors and magnetometers.

Location-based services (LBS) exploit the knowledge of the geographical position of a smartphone in order to provide additional services based on that information. LBS systems generally consist of the following components: a service provider's software application, a mobile network to transmit data and requests for service, a content provider to supply the end user with geo-specific information, a positioning component (GPS), and the end user's mobile device.

2. ABA system description

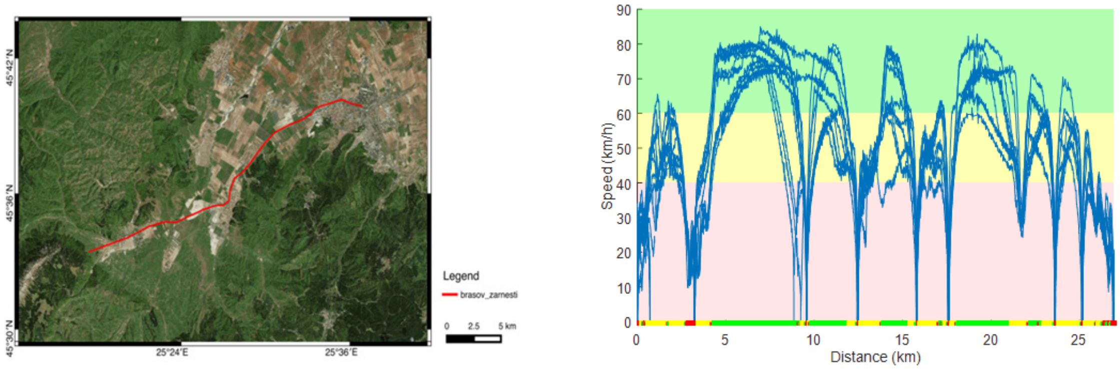
Data is collected from accelerometers, a GPS receiver and either a tacho or speed-sensor for positioning. For ABA measurements, a number of accelerometers are mounted on the axle boxes of at least one bogie. Sensor cables are routed from the bogie frame to the measurement box in the train. GPS data is obtained from a receiver that is 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. 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 are employed when available. In Fig. 1 is the train SNCF Class X 4500, that operates on the line Bartolomeu-Zarnesti. Fig. 1(a) in the workshop of RCCF, Romania. Fig. 2(b) during the measurement campaign in September 2016.

(a)

(b)

Fig. 1 Passenger train employed for ABA measurements in the line near Brasov, Romania: (a) in the workshop of RCCF; (b) in Brasov station during the measuring campaign.

The ABA signal is greatly influenced by the train speed. In the implementation on a passenger train in operation, the speed varied from 0 km/h at stations to up to 80 km/h. The signals collected at nearly 0 km/h do not contain the necessary excitation for analysis of defects, while the ones around 70 km/h will have the more valuable information. In Fig. 2(a) is the map of the railway track measured, and Fig. 2(b) the speed profile at various measurement rounds (from Brasov to Zarnesti). Fig. 2(b) indicates in green the areas where the signals will have the most information usable for detection of defects. The coverage is around 80% of the infrastructure. For the remaining rails (most of them at stations or near them), quantitative relationships with the signature tunes and maximum ABA can be incorporated using a regression model, to make full use of the data collected.



(a) (b)

Fig. 2 (a) Map of the railway track between Brasov and Zarnesti, Romania. (b) Speed of the train during the measuring campaign (various rounds).

3. Ultra low cost smartphones

The proposed system consists of two sub-systems with distinct roles and functions.

Sub-system 1: at rail unit level (application for low cost smartphone), different physical tiers of sub-system consist of

- Android application service for sensor acquisition data,
- Android application gateway for data transmission (Adhoc OR Automatic by Scheduler) via RESTful-service using the phone 3G/4G or WiFi connection,
- basic Android application for local reporting and interrogation data.

Sub-system 2: at Control Centre (application for crowd-data server), different physical tiers of sub-system consist of

- web application for crowd-data server (RESTful service & common database),
- reporting web interface for crowd-data server.

The developed system architecture is presented in the Fig. 3, underlying the different physical tiers (system applications) and connection points. For the design and development of the smartphone application, the most recent and relevant standards and models for measuring passenger comfort were analysed. Many standards for evaluating ride comfort are available such as UIC153, ISO2631-1:1997BS 6841, and ENV-12999. However, after reviewing the standards mentioned, in our case, the best is ISO-2631-1:1997. ISO 2631-1:1997 is the most precise method and has been adopted by most of the countries and railway companies in the world. Perception of ride comfort according to ISO-2631-1:1997 is presented in Table 1. In Table 2, the parameters measured are described.

An important aspect that has been taken into account in the development of the application for the low cost smartphone, was conservation of battery life as a priority to ensure viability of the app. In order to achieve this goal, the processes of the high energy consumption, of the operating system, have been analysed and their use has been optimized as follows.

- Because the acquisition processes from sensors (GPS and accelerometers) are energy-intensive:
  - to acquire the GPS position, it is included the possibility of setting the position refresh (expressed in seconds),
  - the application offers the possibility to set thresholds for the acceleration data to measure passenger comfort or track quality.

- Since the permanent display of the on-screen application interface is the most energy consuming, the application was designed to work in the background during data acquisition.
- Moreover, because the process of data acquisition and storage greatly utilizes the RAM memory of the device (the energy-intensive hard component), these processes have been designed as asynchronous tasks.

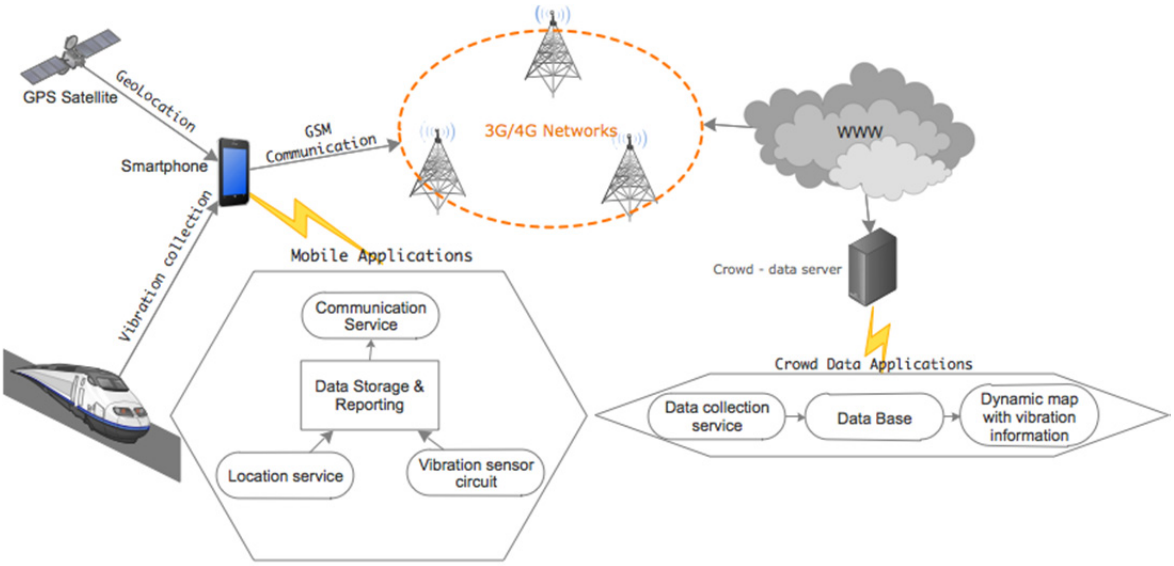


Fig. 3 Architecture for system for track and ride quality monitoring

Table 1. Perception of ride comfort according to ISO-2631-1.

r.m.s vibration level	Perceptions
Less than 0,315 m/s2	Not uncomfortable
0,315 m/s2 to 0,63 m/s2	A little uncomfortable
0,63 m/s2 to 1 m/s2	Fairly uncomfortable
1 m/s2 to 1,6 m/s2	Uncomfortable
1,6 m/s2 to 2,5 m/s2	Very uncomfortable
Greater than 2,5 m/s2	Extremely uncomfortable

Table 2. The parameters of acceleration and orientation sensor built-in smartphone.

Sensor	Data	Description
Acceleration sensor	A_values[0]	Acceleration along the x-axis (including gravity)
	A_values[1]	Acceleration along the y-axis (including gravity)
	A_values[2]	Acceleration along the z-axis (including gravity)
Orientation sensor	O_values[0]	Azimuth, the angle between x-axis and the magnetic North Pole (0° to 360°)
	O_values[1]	Pitch, the angle between y-axis and horizontal plane (−180° to 180°)
	O_values[2]	Roll, the angle between z-axis and horizontal plane (−90° to 90°)

To achieve a 3G/4G or Wi-Fi gateway, a communication module type Android Service was programmed to manage data transmission, remotely to a Control Centre. This module runs in the background and listens to requests for transmitting information, the amount of data requested is sent on the same communications support that was received: GSM or Wi-Fi.

The developed application also provides functions through dedicated graphical controls for:

- database query;
- display information in analysis format;
- commands and queries toward the mobile device, etc.

4. Measurement results

4.1. Results from ABA

The measurements were performed at the end of September 2016. The signals collected cover stations, bridges, rail joints, plain track. In this paper, we discuss the results of condition monitoring of welds. In Fig. 4 are three different welds, labelled as W3, W7 and W11. Side and top views are shown. In Fig. 5 the ABA responses on the welds and the detection signal are presented. Scaled averaged wavelet power is used to detect the welds. In the figure, 5 different measurements are shown. They were all obtained at a similar speed, so it is possible to estimate the severity of the welds based on the energy values or the maximum peak of the ABA signal in the time domain. W11 would be the more healthy weld, while W7 the one where the highest impact and the more energy are concentered among the three welds. This example show that it is possible to create a ranking of the welds that will need more attention in the coming period. Visually they might look in a similar condition; however, by using their dynamic response it is possible to estimate in which ones the more energy is being dissipated during the wheel-weld-track interaction. In the example, the ranking sorted by the more healthy weld would be first W11, second W3 and third W7.

(a) Side view weld W3 (b) Side view weld W7 (c) Side view weld W11

(d) Top view weld W3 (e) Top view weld W7 (f) Top view weld W11

Fig. 4 Three different welds, W3, W7 and W11.

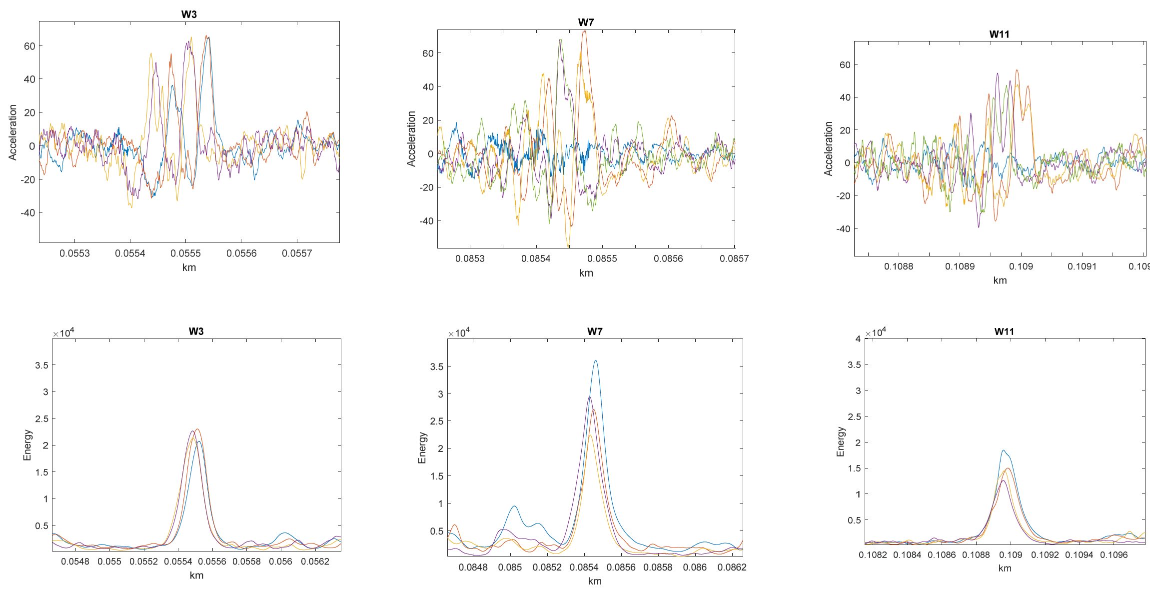


Fig. 5 ABA signal in the time domain and energy for the welds W3, W7 and W11.

4.2. Results from smartphones

The test was performed in Romania on route Bartholomeu – Zarnesti on a passenger train that moved for one hour over a distance of approximately 27 km, in order to check the smartphone's ability to monitor passenger comfort on a train in accordance with the standard ISO-2631-1:1997 and its capability to detect major track failures.

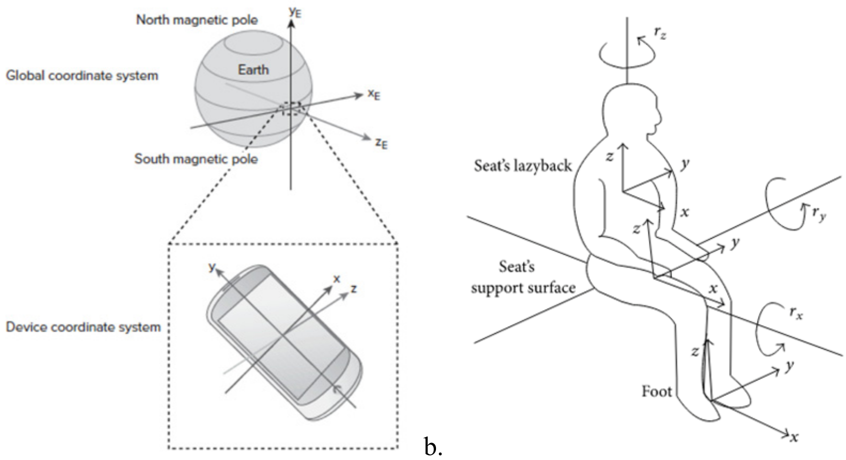
$\varphi\ \theta$

According to standards ISO-2631-1:1997, the weighted root mean squared (rms) acceleration is calculated according to the following formula:

$$a_w(t_0) = \left\{ \frac{1}{\tau} \int_{t_0-\tau}^{t_0} \left[a_w(t) \right]^2 \right\}^{\frac{1}{2}} \tag{1}$$

where $a_w(t)$ is the instantaneous frequency-weighted acceleration (meters per square second), t is the time (seconds), t_0 is the time of observation (seconds), and τ is the integration time for running averaging (seconds).

Another major factor affecting passenger comfort are rotational vibration. A smartphone's coordinate system is a relative coordinate system depending on the smartphone's screen. When the mobile phone is placed horizontally and screen is upward, smartphone's screen center is the origin of this coordinate, the direction parallel to the short side of the screen is the x-axis, the direction parallel to the long side of screen is the y-axis, and the direction vertical up to the screen is the z-axis (see Fig. 6).



a. b.

Fig. 6 (a) Android coordinate systems (Source, Android API Guide) ; (b) Vibration model of human body (Source, Hong et al., 2016).

The calculation of total weighted acceleration RMS for a specific moment of time T is shown in following formula:

$$a_{wT} = \sqrt{(1.4a_{wx})^2 + (1.4a_{wy})^2 + (a_{wz})^2} \tag{2}$$

where a_{wx} , a_{wy}, a_{wz} and are weighted acceleration RMS of each axials, respectively, and coefficient 1,4 is the ratio of the vertical, longitudinal, and horizontal corresponding frequency weighted curve in the range of human body's most sensitive frequency.

For the roll and pitch angles. we are using the subscript y, x, z to denote that the angles are computed according to the rotation sequence:

$$\tan(\phi_{xyz}) = \frac{a_{wy}}{\sqrt{a_{wx}^2 + a_{wz}^2}} \tag{3}$$

$$\tan(\theta_{xyz}) = \frac{-a_{wx}}{\sqrt{a_{wy}^2 + a_{wz}^2}} \tag{4}$$

Vibrations in trains can be caused by welding and rolling defects, rail joints, poor track alignments, various defects/roughness in the track or wheel surfaces, etc. Other factor that affect the signals is the speed of the train. High speed magnifies the amplitude of the vibrations. These and other variables affect the perception of ride comfort from the passengers point of view. Fig. 7 and Fig. 8 show the most relevant results, in which the vibration and comfort records are presented.

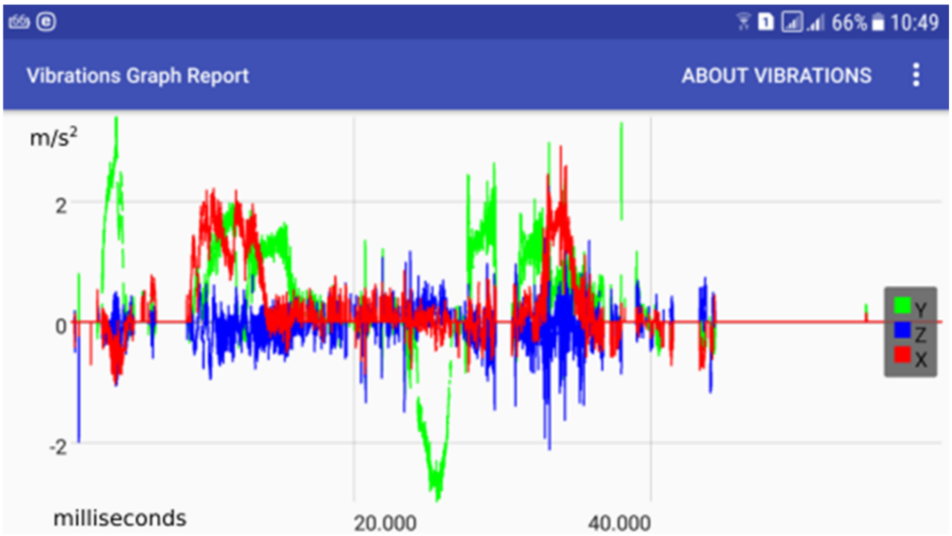


Fig. 7 Vibration diagram.

Fig. 8 Comfort and rotational acceleration diagram.

As a result of the research carried out, it has been observed that comfort is influenced by the following aspects:

- **Rail bridges** – crossing over them can have adverse effects on ride comfort.
- **Speed traveling** - when traveling at low speeds the impact on ride comfort from the bridge itself is quite low, rather the condition of the track has the largest impact on ride comfort.
- **Stiffness of the bridge supports -** ride comfort linearly increases with the stiffness of the bridge supports. Motions induced by the train on to the bridge can cause discomfort among passengers in the form of vertical and rotational acceleration.
- **Switches and crossings –** Passing over S&C induces motions (increase in vertical vibrations) in the train due to the rail track discontinuity in this point. In the case of divergent route of **deteriorated turnouts** a significantly increase in the vibration amplitude can be observed.
- **Turns and curves** - train turns induces motions (increase in rotational vibration, see Fig. 8); this vibration is generally induced due to the presence of cants (where one half of the track is super elevated), which enable trains to maintain higher speeds while traversing the curve

5. Conclusions

In this paper, one methodology for detection of short waves defects and one methodology for detection of long waves defects are used for estimating track and ride quality: axle box acceleration measurements and ultra-low cost smartphones. Both methodologies are based on accelerometers mounted either at the axle box or in the train vehicle. Both required coordination with other signals such as GPS, for positioning. The information collected from both systems contains useful information for the inframanagers. With ABA, it is possible (among other applications) to rank the quality of the welds and also of other defects. With the smartphone technology it is possible to map over the network the ride comfort, which is important for the users and for the safety.

The collected data can be used for modelling, analysis, for supporting decision making of maintenance, but following a paradigm different from other traditional/old systems. From the theoretical and practical points of view, use of railway infrastructure information is challenging because it is multidimensional, spatially and temporally distributed, multi-scale, and it comes from heterogeneous data sources.

With adaptive and intelligent signal processing methods, it is possible to extract the key information needed for the decision-making process to anticipate the impact of degradation and determine the control measures needed to correct the problems in the infrastructure. Part of the further research is the generation of meaningful maintenance rules for the decision making of inframanagers using the collected track and quality information.

Acknowledgements

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6. References

Android API Guide, http://developer.android.com/reference/android/hardware/SensorEvent.html

Bocciolone, M., Caprioli, A., Cigada, A., and Collina, A., 2007. A measurement system for quick rail inspection and effective track maintenance strategy. Mechanical Systems and Signal Processing 21(3), 1242-1254.

Hong, Z., Li-Lu, G., and Xiang-Yan, Z., 2016. Evaluation of bus vibration comfort based on passenger crowdsourcing mode. Mathematical Problems in Engineering 2016, ID 2132454, 10 pages.

Lee, J.S., Choi, S., Kim, S.S., Park, C., and Kim, Y. G., 2012. A mixed filtering approach for track condition monitoring using accelerometers on the axle box and bogie. IEEE Transactions on Instrumentation and Measurement 61(3), 749-758.

Li, Z., Dollevoet, R., Molodova, M., and Zhao, X., 2011. Squat growth—Some observations and the validation of numerical predictions. Wear 271(1–2), 148-157.

Li, Z., Molodova, M., Núñez, A., and Dollevoet, R., 2015. Improvements in axle box acceleration measurements for the detection of light squats in railway infrastructure. IEEE Transactions on Industrial Electronics 62(7), 4385-4397.

Lichtberger, B., 2007. The track system and its maintenance. RTR Special on Maintenance & Renewal 2007, 14-22.

Massel, A., 1999. Power spectrum analysis—modern tool in the study of rail surface corrugations. NDT & E International 32(8), 429-436.

Molodova, M., Li, Z., and Dollevoet, R., 2011. Axle box acceleration: Measurement and simulation for detection of short track defects. Wear 271(1–2), 349-356.

Molodova, M., Li, Z., Núñez, A., and Dollevoet, R., 2014. Automatic detection of squats in the railway infrastructures. IEEE Transactions on Intelligent Transportation Systems 15(5), 1980-1990.

Molodova, M., Oregui, M., Núñez, A., Li, Z., and Dollevoet, R., 2016. Health condition monitoring of insulated joints based on axle box acceleration measurements. Engineering Structures 123(2016), 225-235.

Oregui, M., Molodova, M., Núñez, A., Dollevoet, R., and Li, Z., 2015. Experimental investigation into the condition of insulated rail joints by impact excitation. Experimental Mechanics 55(9), 1597-1612.

Sunaga, Y., Sano, I., and Ide, T., 1997. A practical use of axlebox acceleration to control the short wave track irregularities. Florence, Italy: in Proceedings of the World Congress on Railway Research, 16-19 November, 1997.

Veit, P., 2007. Track quality - luxury or necessity? RTR Special Maintenance & Renewal, 2007.

Z. Wei, A. Núñez, Z. Li and R. Dollevoet, 2017. Evaluating degradation at railway crossings using axle box acceleration measurements. Sensors 2017 17(10), 2236, DOI: 10.3390/s17102236