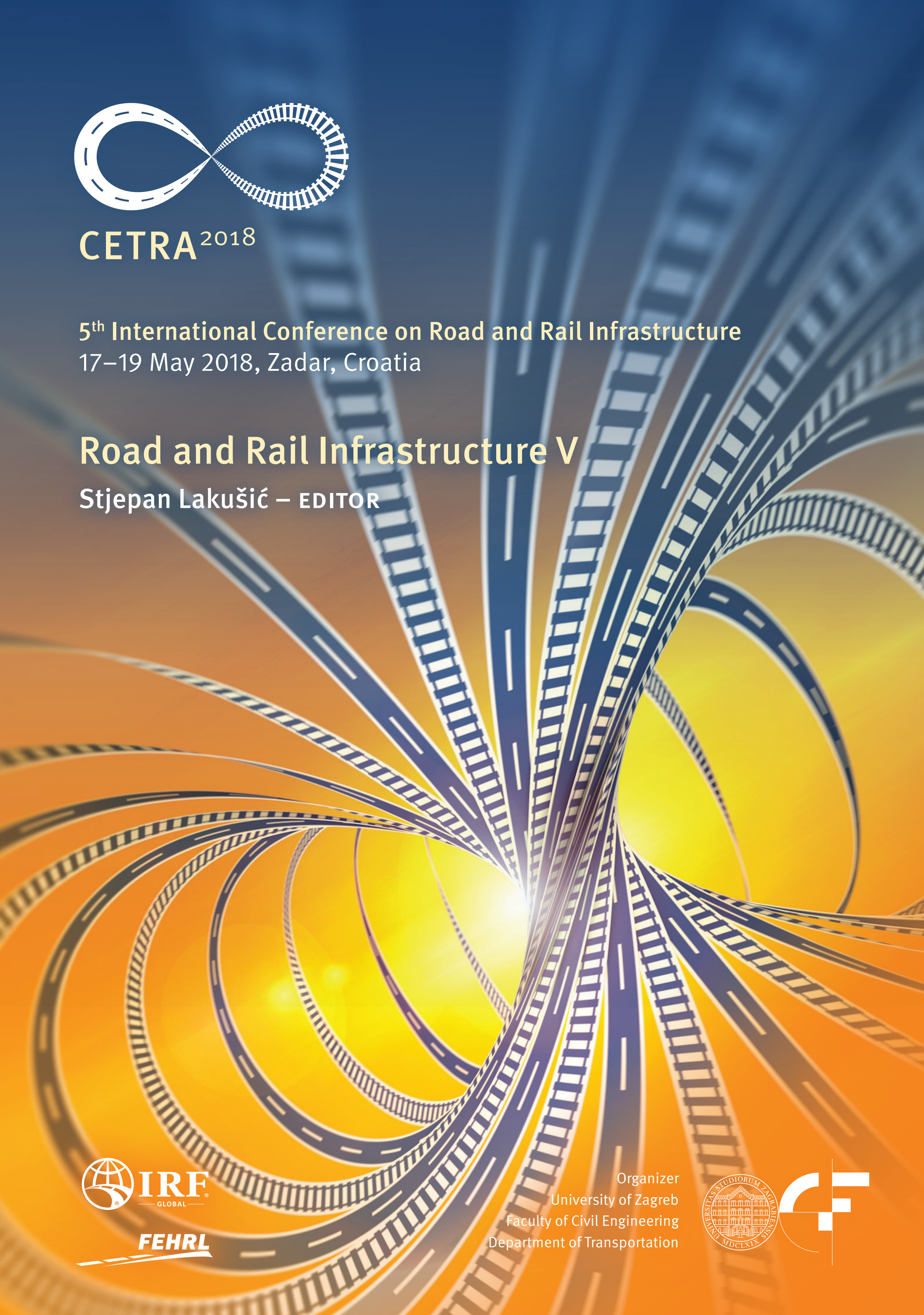

CETRA 2018

5th International Conference on Road and Rail Infrastructure
17–19 May 2018, Zadar, Croatia

Road and Rail Infrastructure V

Stjepan Lakušić – **EDITOR**

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VIBRATION-BASED CONDITION MONITORING OF TRAMWAY TRACK FROM IN SERVICE VEHICLE USING TIME-FREQUENCY PROCESSING TECHNIQUES

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Abstract

Until now, the automatic under load condition monitoring of tramway's track has not been applied in Hungary. Due to the lack of track recording car, only the visual inspection on track was used for identifying track defects. This paper presents automatic methods for detecting track irregularities on tramway operation using acceleration measurements on tram. For monitoring of tramway tracks, an unconventional measurement set-up is developed, which records the data of 3-axes wireless accelerometers mounted on wheel discs. Accelerations are processed to determine whether the track needs to be repaired from the obtained vibration behaviour of track-vehicle dynamic interaction. New track parameters are developed for determining the location of the defect and assessing the level of deterioration, which are generated by automatic detection algorithms based on time–frequency distribution analysis. Furthermore, a new Track Quality Index (denoted "DMSZ") is developed, which is calculated from the developed parameters to summarize and display the condition of large sections of track. The method was validated on frequented tram lines in Budapest, where track sections in moderate and in serious condition were accurately detected.

Keywords: tramway track condition monitoring, track quality index, vibration, wheel-mounted accelerometer, time-frequency processing techniques

1 Introduction

The responsibility of Railway Companies is to provide a certain level of service meeting the safety and ride comfort requirements. Systematic and periodical inspections must be performed to keep the tracks in good condition. The worldwide used techniques for railway track condition monitoring can provide different levels of service. Subjective track quality scoring is only suitable for identifying safety-critical defects. Un-load track geometry measurement-based assessment works well in the case of controlling newly-built track alignment, but the rolling stock measurements-based condition assessment is absolutely necessary for planning preventive maintenance activity [1]. In tramway operation due to both the frequent rail- and road vehicle traffic volumes, the track quality can be changed rapidly and often there is no time available to carry out the inspections necessary to determine track condition. Therefore, in-service vehicles equipped with inertial sensors may serve an effective system for monitoring the entire railway infrastructure on a daily basis with continuous updates at a relatively low cost.
This paper presents the first results of an inertial sensor based new measurement set-up for monitoring tramway track that is based on a prototype designed by Authors [2], and that was implemented and validated via extensive field tests on the Budapest tram tracks. In the mo-

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nitoring system accelerometers mounted on the wheel discs are applied to obtain vibration behaviour of track-vehicle interaction and determine whether the track needs to be repaired. For the new measurement set-up new track parameters are developed using time–frequency distribution analysis. Furthermore, a new Track Quality Index (denoted in Hungarian DMSZ) is developed, which calculated from the developed parameters to summarize and display the condition of large sections of track. The method was validated on frequented tram lines in Budapest, where track sections in moderate and serious condition were accurately detected. In the next section details are given about the measurement set-up adopted for experiments with the instrumented tram. In section 3 the calibration of the new measurement system is discussed. Section 4 presents the algorithms applied for detecting isolated track irregularities. Then, section 5 introduces the new track quality index and it is intended to face the test results and gives the main conclusions on the considered possibilities for development of the currently used tramway track condition monitoring.

2 Measurement system and Data acquisition

A prototype of the measurement system has been installed on a specialised recording tram. A GANZ type articulated tramcar was instrumented, which has 3 body sections, two not-driven Jacobs-type bogies and two driven bogies, one at each end of the vehicle.
Three-axes accelerometers are mounted on each wheel disc within a not-driven bogie, and on the middle part of the bogie side-frames under the pivot point of car body. The applied sensors were calibrated by the manufacturer to comply with the accuracy standards. The sampling frequency (Fs) of the acceleration sensors were 400 Hz. Taking the speed range between 0-50 km/h, the maximum scale of acceleration recorded by this measurement set-up is ±20 g on a rotating wheel and bogie side-frame and ±1g on the car body. Therefore, the scale of sensors on the wheels and the bogie side frame were set to ±24 g and the car body sensors to ±6 g. The sensors on wheel sense the a_z axial acceleration pointing outward from the plane of wheel, the a_x tangential acceleration and a_y radial acceleration. Pre-processing of this data is required to remove components from rotation and convert the data to meaningful quasi-vertical and compensated lateral wheel acceleration.

2.1 Quasi-vertical wheel acceleration

The use of rotating wheel mounted accelerometers requires a pre-processing method, in which quasi-vertical acceleration is calculated from the tangential and radial acceleration components recorded on wheel according to Eq. (1):

$$Q = a_{y,\mathrm{filt}} \cdot \sin\theta_{\mathrm{angle}} + a_{x,\mathrm{filt}} \cdot \cos\theta_{\mathrm{angle}} \tag{1}$$

Where:
Q – quasi-vertical wheel acceleration;
$a_{x,\mathrm{filt}}$ – high-pass filtered tangential acceleration (f_{cut} = 0,5 Hz);
$a_{y,\mathrm{filt}}$ – high-pass filtered radial acceleration (f_{cut} = 0,5 Hz);
θ_{angle} – rotation angle of wheel calculated by Eq. (2):

$$\theta_{\mathrm{angle}} = \arctan\left(\frac{a_{gy}}{a_{gx}}\right) \tag{2}$$

Where a_{gy} is the gravity component of radial acceleration [g]; a_{gx} is the gravity component of tangential acceleration [g]. The Q parameter is one of the main input data of the automatic track defects detecting algorithms.

2.2 Localisation

The localisation of recorded data is identified by using tachometer signal of powered axle and GPS navigation devices. It should be noted that the travelled route can also be computed only from recorded wheel accelerations [2, 3] because they can work as a revolution counter. After applying a low-pass filter (f_c = 5 Hz) on both y and x axes of wheel sensors to isolate the gravitational component, the rotated angle can be computed by using these components according to Eq. (2). During the calculation the real wheel diameter is taken into account. The accuracy of the computed position information depends on both the total travelled route, the number of wheel slips and the vehicle riding quality, but it provides sufficient accuracy for finding the defects by visual inspection along the track.

3 Calibration

The results of the developed condition monitoring method depend on both sub-systems of vehicle-track interaction. Therefore, a calibration process is carried out and requirements are defined by the Authors for controlling the condition of the instrumented vehicle. The accuracy of the measurement system is investigated in a tram depot in Budapest, where various runs are made along the same track in the same direction starting with same and opposite ends of the vehicle. Keeping the velocity of the vehicle constant between runs, we expect the sensors on same side must record nearly equal data. The test section includes Grooved Rail Turnouts, and reverse curves, which make extensive testing of the riding performance of the instrumented vehicle possible.

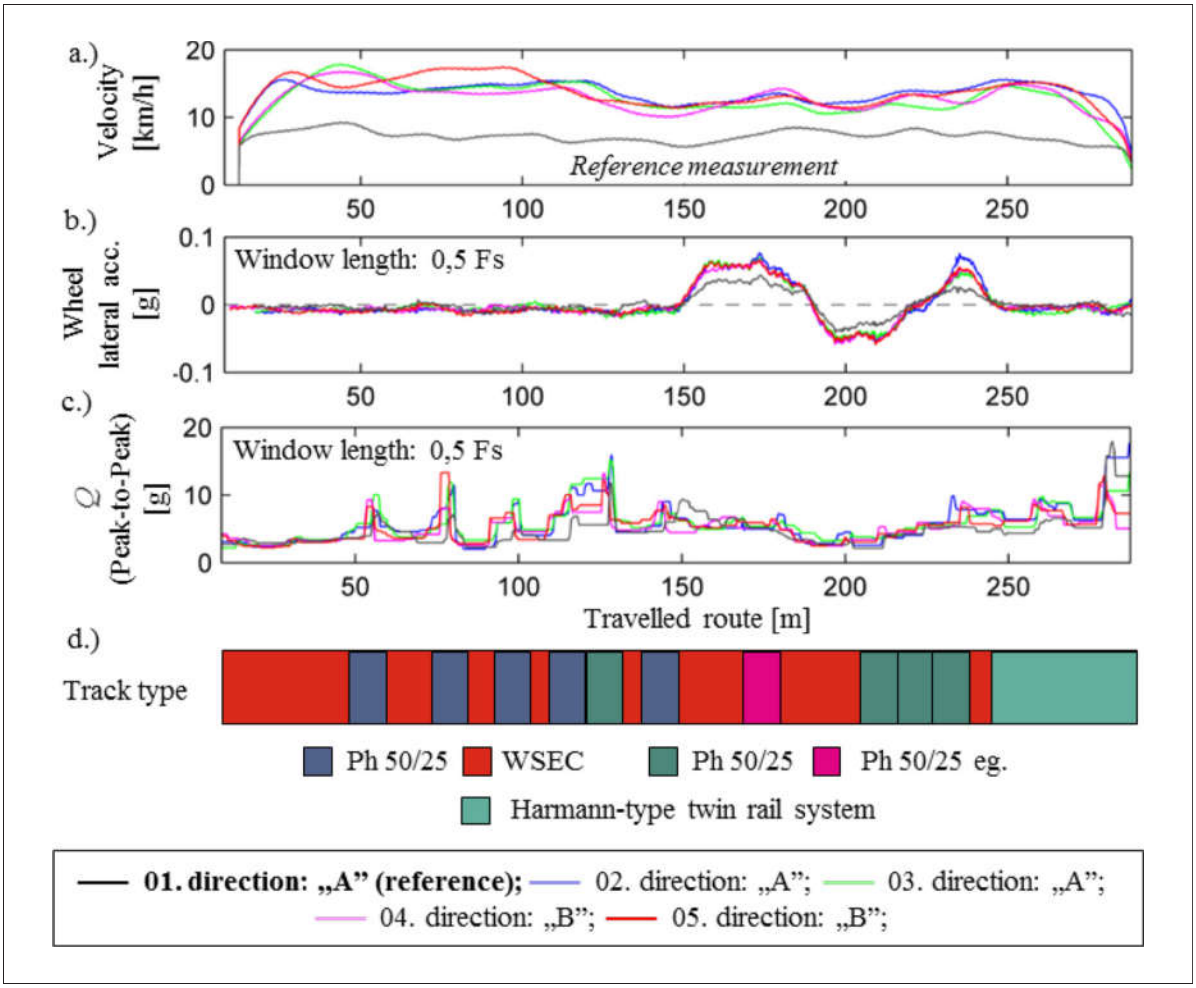

Figure 1 Comparison of the recorded wheel accelerations passing with same and opposite ends of vehicle ("A" and "B")

Figure 1. presents five runs made on same track. The first one is the reference measurement at a constant speed of 9 km/h and the others are carried out at 15 km/h. The diagram b.) on Figure 1. shows the calculated moving average of the recorded lateral wheel acceleration using 0,5 Fs window length, while diagram c.) represents the peak-to-peak amplitude of quasi-vertical acceleration using same windows length. Diagram d.) represents the track types along the track section (WSEC: Wooden Sleeper embedded in concrete).

The difference of the lateral wheel acceleration recorded by passing both the same and the opposite end of the vehicle is less than 0,010 g (Figure 1b). Only measurement no. 02 has a higher difference between 230 and 240 m.

The peaks on Figure 1c between 50 and 150 m refer to the vertical additional loads forming on spatial partial flange bearing frogs of turnouts. The average peak-to-peak difference between recorded data passing with same ends of vehicle is 1,0 – 1,4 g on turnouts, while passing with opposite end of vehicle it is 2,1 – 2,3 g. This difference is much more favorable on those sections, where there is no object on the track: passing with the same vehicle end, it is 0,29 – 0,67 g, while passing with opposite vehicle end it is 1,59 – 1,72 g. It can be concluded that the runs passed on the same track starting with the same ends of the vehicle can be applied for monitoring of tracks.

4 Assessment of track

In track quality assessment, the isolated defects and the track sections with certain length are separately analysed. New track parameters are developed for analysing local defects using the recorded data of the new measurement setup. The applied automatic detection algorithms are based on time–frequency distribution analysis.

4.1 Derailment safety measurement number

The track twist is the most dangerous track defect. Derailment risk can be occurred on track twist, when high lateral guiding force formed, in addition to reduced wheel vertical load. Therefore, the ratio of the lateral and quasi-vertical wheel acceleration refers to derailment risk. However, the calculated index will be valid only for the instrumented vehicle, because its structural design has a significant impact on it. Due to rigid axles within the instrumented bogie we can distinguish three different cases depending on which wheel is unloaded within the bogie. All cases are analysed in each time step and the maximum value is selected according to Eq. (3).

$$\mathrm{SiklB} = \max \begin{bmatrix} \left|Z_{FL} - Z_{FR}\right| \cdot \left(1 - Q_{FL,\text{ or }FR}\right)^2 \\ \left|Z_{RL} - Z_{FR}\right| \cdot \left(1 - Q_{RL,\text{ or }FR}\right)^2 \\ \left|Z_{FL} - Z_{RR}\right| \cdot \left(1 - Q_{FL,\text{ or }RR}\right)^2 \end{bmatrix} \tag{3}$$

Where SiklB is the derailment safety index; Z and Q is the low-pass filtered (f_{cut} = 15 Hz) lateral and quasi-vertical acceleration of the wheels in different positions according to direction of travel: RL: rear left; RR: rear right; FR: front right; FL: front left.

4.2 Vertical track load measurement number

After using the pre-processing method discussed in section 2, the frequency averaged STFT (Short time Fourier Transform) power spectrum is calculated from the quasi-vertical wheel accelerations of the first axle, which is decomposed into two components using the baseline estimation method denoted “BEADS” (Baseline Estimation and Denoising with Sparsity) [4]. The baseline represents the back-ground noise of the signal, which depends on the elasticity of the different track structures and the technical state of vehicle, so removing this part, a super-structure-independent evaluation can be carried out according to Eq. (4).

$$\mathrm{Fptj} = \frac{(\hat{S}_{Q,FL} - \hat{f}_{Q,FL}) + (\hat{S}_{Q,FR} - \hat{f}_{Q,FR})}{2} \tag{4}$$

Where:
Fptj – vertical track load measurement number;
$\hat{S}$ – frequency averaged STFT power spectrum;
$\hat{f}$ – estimated baseline using BEADS algorithm [4];
Q_{FL}; Q_{FR} – front left and right quasi-vertical wheel acceleration according to travelling direction.

After removing the baseline, the residual part refers to additional loads between the wheel and rail. The regularization parameters (λ, $\in$ and r) of baseline estimation have been empirically determined with several systematic settings in such a way that the “defects” identified by visual observation along a reference track section could be detected. The reference measurement was carried out in a tram depot in Budapest, where spatial partial flange bearing frogs of grooved rail turnouts caused additional vertical load on wheels. The developed algorithm accurately detected the locations of the additional loads discussed above.

4.3 Intensity of corrugation on rail top level

The intensity of vertical load from corrugation on the rail top surface can be calculated from the same side wheel quasi-vertical, and bogie side-frame vertical acceleration using maximum median quotients of the STFT power spectrum over time windows and considering the vibration amplitude multiplying factor according to Eq. (5):

$$\mathrm{Hkop}_{B,J}(i) = \left(\frac{\hat{S}_{max}(i)}{\hat{S}_{median}(i)} - \mu_{MaMe} \right) \cdot \log_{10}(\hat{S}_{max}(i) - \hat{S}_{median}(i)) \tag{5}$$

Where:
$\mathrm{Hkop}_{B,J}$ – intensity of rail corrugation on top surface of left or right rail;
i – serial number of current time window (0,5 Fs “Hanning window”; 0,4 Fs timestep);
μ_{MaMe} – expected value of $\hat{S}_{max}/\hat{S}_{median}$ on non-corrugated straight rail, $\mu_{MaMe} = 2,5$;
$\hat{S}_{max}$ – max value of STFT power spectrum calculated per time windows from same side wheel quasi-vertical and bogie vertical acceleration Eq. (6);
$\hat{S}_{median}$ – median value of STFT power spectrum calculated per time windows from same side wheel quasi-vertical and bogie vertical acceleration Eq. (6):

$$\hat{S}_j(i) = \frac{S_{j,F}(i) + S_{j,FW}(i) + S_{j,RW}(i)}{3} \tag{6}$$

Where:
j – median, or maximum;
F – vertical bogie side frame acceleration;
FW, RW – front and rear quasi-vertical wheel acceleration according to travel direction.

4.4 Transversal travel comfort

In lateral direction the suspension of the instrumented vehicle can be considered as a rigid connection, so lateral acceleration recorded on distinct parts of vehicle represents the additional loads in the transversal direction. The lateral acceleration measured on the car body’s floor is low-pass filtered using a 3rd order Butterworth filter with a 10 Hz cut-off frequency. Transversal travel comfort is determined from this filtered acceleration, by applying a sliding window with a 0,5 s·Fs length and calculating the peak-to-peak amplitudes.

5 DMSZ: The new additive Track Quality Index

This index is based on the computed area of the region bounded by the graphs of the developed parameters (see section 4) over certain lengths of track segments. Area is calculated for each parameter and the weighted average value of them gives the general DMSZ value of the current segment according to Eq. (7):

$$\mathrm{DMSZ}_h = \frac{\sum^{h}\mathrm{Fptj} + 300\cdot\sum^{h}\mathrm{SiklB} + \sum^{h}\mathrm{Kuk} + 3\cdot\sum^{h}\mathrm{Hkop}}{4} \tag{7}$$

Where:
DMSZ_h – Track Quality Index on the current track segment;
h – length of track segment (h = 6 m);
Fptj – vertical track load measurement number;
SiklB – derailment safety measurement number;
Kuk – transversal travel comfort;
Hkop – average intensity of left and right rail corrugation.

The weights of parameters in Eq. (7). equalizes the area under the graphs in addition to give higher priority for the derailment risk compared to other parameters. The length of the track segments is set 6 m. Figure 3. shows the calculated track quality index on tram line 51 in Budapest, where Slab Track system with Block Rail can be found in different conditions. This track was visually inspected and three sections with different levels of deterioration (Section A: good, Section B: average and Section C: poor condition) were distinguished. The distribution function of the calculated DMSZ values (measurement made on 2017.06.07) also represents the condition of these segments (see Figure 2.).

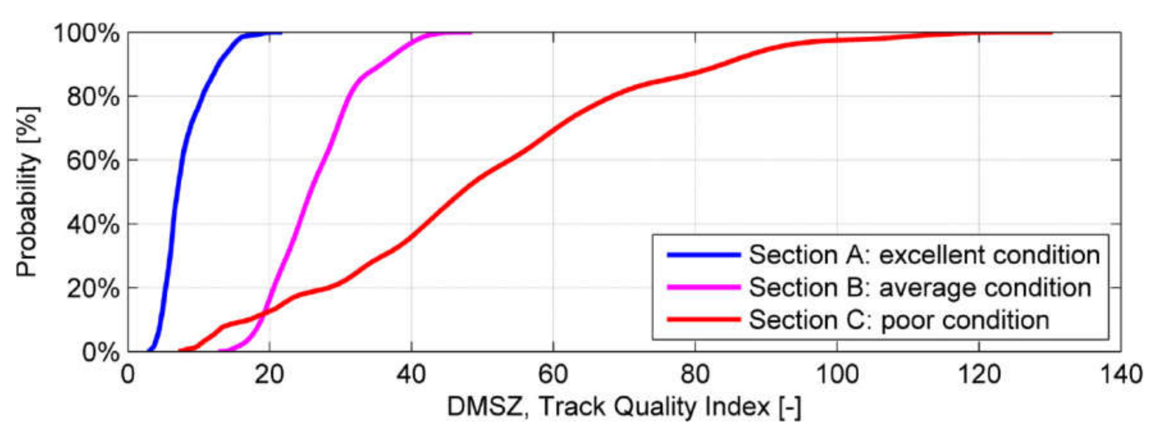

Figure 2 The distribution function of the calculated DMSZ value on track sections in different condition identified by visual inspection along the track (Tram line 51 in Budapest, measured on 2017.06.07. before reconstruction of Section C, see red curves on Figure 3.)

Section A and Section B were rebuilt in 2013, but on section B the existing slab panels were repaired and reconstructed, while in Section A newly manufactured panels were used. On Section C vertical and lateral track irregularities can be found at the joining panels and the wheel flange is often in contact with the bottom of the groove part of the block rail. This section was reconstructed in 2017 and the track inspection was repeated after reconstruction (2017.12.10). On Figure 3. you can see significant changes in DMSZ value on the reconstructed section between 300 and 800 m. Both the lateral acceleration recorded on the wheel and the DMSZ value after the position of 800 m don't show significant changes between the two inspections.

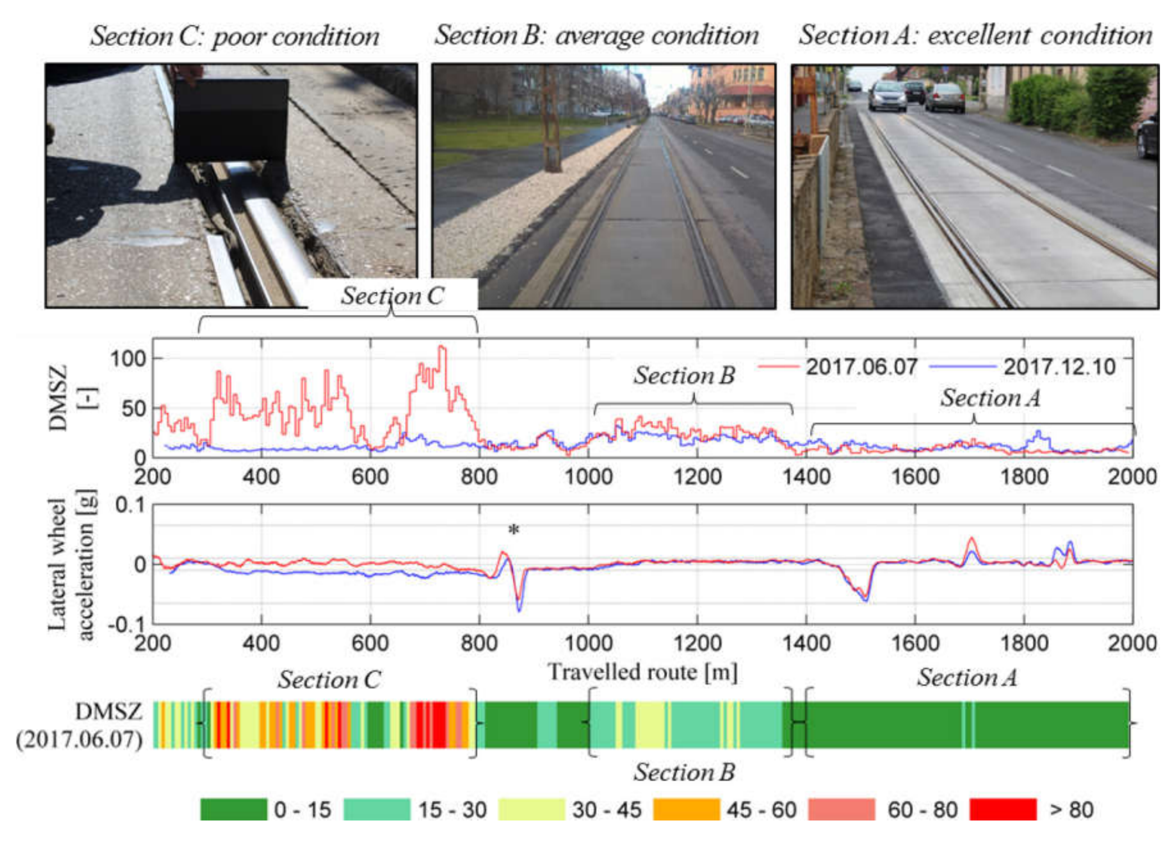

Figure 3 Track quality assessment on Tram line 51 (h = 6 m). Section A: 800 – 1000 m* and 1400 – 1980 m; Section B: 1000 – 1350 m; Section C: track section in poor condition before reconstruction, 300 – 800 m.

6 Conclusion

Although the introduced vehicle dynamics measurement system does not provide exact data of track geometry, the developed parameters are able to detect poor track geometry and structural problems (faulted welds, fastenings and rail joints, foundation problems).
The track segments in different conditions selected by visual inspection along the track can also be distinguished by the developed new Track Quality Index. Furthermore, the half-year later repeated track inspection accurately showed the changes in the deterioration level of the track.
The instrumented vehicle works now as a specialised recording car, in order to analyse the influencing factors on the system, but the plan is to mount this prototype on in-service trams to provide an effective system for monitoring the entire railway infrastructure on a daily basis with continuous updates at a relatively low cost.

References

[1] Roberts, C., Goodall, R.M.: “Strategies and techniques for safety and performance monitoring on railways”. IFAC Proceedings Volumes, 42(8), pp. 746–755. 2009. DOI:10.3182/20090630-4-ES-2003.00123

[2] Vinkó, Á.: Monitoring and condition assessment of tramway track using in-service vehicle. Pollack Periodica, 11(3), pp. 73-82, 2016. DOI: 10.1556/606.2016.11.3.7

[3] Vinkó, Á., Bocz, P.: “Practical experience and in-service vehicle dynamics measurements based maintenance strategy for Tramways Infrastructure.” In: Proceedings of International Conference on Road and Rail Infrastructure – CETRA 2016 (ed. Lakusic, S.), Šibenik, Croatia, 23-25 May, 2016, pp. 335-341. ISSN: 1848-9842.

[4] Ning, X., Selesnick, I.W., Duval, L.: “Chromatogram baseline estimation and denoising using sparsity (BEADS)”. Chemometrics and Intelligent Laboratory Systems, 139, pp. 156–167. 2014. DOI: 10.1016/j.chemolab.2014.09.014.