Thesis booklet

Signal processing technique-based tramway track condition monitoring method and the examination of the system dependencies

Ph.D. dissertation

Author:
Ákos Vinkó,
MSc. in Civil Engineering

Supervisor:
Dr. Péter BOCZ PhD, associate professor

Co-supervisor:
Dr. Gyula KORMOS, honorary associate professor

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1. Introduction

1.1. Overview, importance of the topic

The methods and instruments of track condition assessment have been steadily developed over the years. First only visual observation and practical experience are used for determining track quality. This type of assessment highly depends on the person, who performs the evaluation, even if the multi-criteria track rating system is well-developed. Therefore, the measurements-based assessments have been developed, which ensure the objective estimation of track quality. The first measuring systems were only suitable to measure parameters of un-loaded track and over time track recording cars were developed, which were able to measure track in loaded state. Since the beginning of the use of computational technology for track diagnostics huge amount of data have been accumulated at the railway operators and data processing has always required the use of state-of-the-art technology available. Nowadays there is a great variety of track measuring devices and methods available: from track geometry recoding trollies to track recording cars [1–5].

The measurement systems can be divided into two large groups depending on which part of the track-vehicle system is measured: for inspection of wheelset condition (flat wheel, overheating axle bearing, uneven wheel load) the track-side sensors are used, while the vehicle-mounted sensors are preferred if we want to get information about track quality. According to the type of applied sensors we can distinguish rail diagnostic methods, track geometry and inertial measurement systems.

Rail diagnostic methods mainly using ultrasonic and eddy current technology to identify the rail defects both on rail top level and inside of the rail head.

The track geometry measuring systems provide distortion-free data of track geometry using contact, or non-contact technologies. There is a close relation between the current geometrical deviation of track structural elements and the track deterioration level, thus the track quality can be well assessed by geometric deviation from ideal condition. Geometrical deviations are usually formed at the start phase of the track deterioration process, while as time went on the structural and then fatigue defects can also be formed due to the cyclical
loads from vehicles. However, the track geometry measuring systems can not take into account the dynamical response measured by passing through the given track irregularity, which plays an important rule in the formation of structural problems of track components. Therefore, the simultaneously measured dynamic additional load of vehicle should also be considered in the determination of the admissible limits for track geometry [6].

The vehicle dynamics measuring systems measure the vehicle side loads, which cyclic repetition causes the material fatigue and failure of the track's structural elements. The axle-box [7–12], bogie side-frame and car body mounted inertial sensors [12–15] are commonly used for measuring vehicle dynamics behaviour. Due to the behaviour of the vehicle as a mass-spring system, the measurements are performed in a speed range above 100 km / h, which provides the isolation between the excitation generated by track components and the resulting structural characteristics of the vehicle excitations. The Europe-wide used and standardized vehicle dynamics measurement systems mainly suited only to determine the derailment safety, running stability, ride quality and passenger comfort metrics.

A recently used new method for track condition assessment is based on the vibration analysis of the vehicle-track interaction [16] and the statistical evaluation of measured data. When the vehicle passing true a track defect, the forming irregular movement of wheelset can cause the excitation of the structural components of the vehicle. The irregular vehicle movement can refer to track irregularities and depending on the defect type different exciter frequency components are registered in the measured signal. There are numerous solutions in literature to detect different wavelength-track defects by using the techniques of signal processing.

The main objective of track inspection is to identify the track quality from the recorded track parameters either using track quality indexes over certain track length or using statistical analysis of recorded data exceeded the admissible limits. Statistical evaluation of a large number of track measurements is required for both determining admissible limits of track parameters for different service levels (alarm-, intervention-, immeditally action limit) and the optimum length used for track quality index. The track geometry measuring, and assessment system is well-developed and widely accepted. The automatic under load condition monitoring of tram-way’s track
has not been applied in Hungary due to the lack of track recording car. Nowadays, the Hungarian practice of tramway track condition assessment is only suitable for identifying safety-critical defects, which are detected during visual inspection on track. The organization of maintenance work is largely based on subjective professional experience.

The existing solutions have demonstrated to be reliable in conventional railways, but due the special characteristics of tramway operation including both the track and the significant variation of the vehicle infrastructure make it necessary to examine the applicability of the methods.

The current national [17] and international standards for track geometry and vehicle dynamic measurements (European [18] [19], North-America [20], Australian [21]) do not exclude the application of the methods on tramways. Thus, the development of a state-of-the-art measuring method and qualification procedure for tramway track condition assessment is clearly an important task.

1.2. The goals of research

This dissertation is concerned with the development of an inertial method for tramway track condition monitoring from in-service vehicle using the techniques of signal processing, which does not require a significant change in the structural design of the instrumented vehicle and in the speed range used in the tramway operation, it is suitable for identifying the track defects and reliably representing the change in track quality. The main objectives of my work in accordance with the above:

- The developing new parameters based on vibration analysis of wheel-rail contact be matched to the widely used track geometry parameters in order to the recorded track geometry be comparable to the vehicle dynamics measurements;
- The objective of the dissertation is not regarding to determine the accurate track geometry in "mm" dimension, but the localisation of track defects and the scoring their relative severity is required independently from track structures;
• Determining the dependence of the measuring system in relation to the measurement speed, vehicle technical condition and the elasticity of the types of superstructure used on tramways;
• Development of the calibration method of the measuring system;
• Proposed limits for the elaborated track quality parameters.

1.3. Outline of dissertation

Based on the introduction the research has the ambition of developing a new method for tramway track condition monitoring from in-service vehicle and introducing the system dependencies considering the characteristics of both the rolling stock and track infrastructure used in tramway operation. The dissertation contains 8 main chapters.

The first part of the research – Chapters 2., 3., 4., 5. – provides a literature review of the types of inertial measuring systems used in conventional railways and deal with their most important parameters supplied and introduces the relevant regulations.

The second part of the dissertation – Chapters 6., 7., 8. – presents the developed new methods for tramway track condition monitoring. As long as there are no sufficient measurement data from vehicle dynamics measurements available, the developed un-loaded measurement methods can provide an opportunity to verify and validate the data of dynamic measurements.

Chapter 2 introduces the general aspects of the placement and selection of inertial sensors according to the literature and gives the critical evaluation of the currently used measurement arrangements.

Chapter 3 describes the theoretical background of the methods used in the research, Chapter 4 summarizes the domestic and international standards governing the evaluation of data provided by the inertial measurement systems (derailmant safety, running stubility, ride comfort), while Chapter 5 describes foreign application examples and their most important technical parameters.

In Chapter 6 I collected the special defect types of the tramway track structures, and I identified the causes of their development by various type of field measurements and visual observations. Based on the collected experiences, I developed a quasi-objective (based on unlade track geometric measurements) and a subjective (based on visual track inspection by walking along the line) track condition assessment method. I also developed a data
structure and an online failure registration form to store the identified track defects in a database. However, in planning a preventive maintenance work, it is required to use such condition monitoring methods which are able to record the track parameters in loaded state besides the subjective and quasi-objective condition assessment methods.

Chapter 7, accordingly, describes the new condition monitoring method for tramway tracks, which is significantly different from conventional solutions in the measurement arrangement since the accelerometer sensors are fixed to the rotating wheel. The developed measuring system has been installed on a GANZ type articulated tramcar (hereinafter referred to as ICS), which has been out of passenger service. The construction of the measuring system was carried out in cooperation with the experts of both METALELEKTRO Measuring Technique Ltd. and Budapest Public Transport Ltd. Although the introduced vehicle dynamics measurement system does not provide exact data of track geometry, but at low speed (10 to 50 km / h), it is suitable for detecting such track defects that require maintenance intervention due to the additional load formed from rotating wheel. 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 and the actual wheel diameter, because the sensors can work as a revolution counter.

Chapter 8 describes the developed evaluation methods of track quality, in which 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. Since the identification of track defects is based on the detection of vibrations between the wheel and the rail, the elaborated algorithms allow the separation of the vibrations generated by the track defects and other vibrations resulting from the structural properties of the vehicle. The applied automatic detection algorithms are based on time–frequency distribution analysis. The evaluation of local defects is based on the data exceeded the limits of the formed excitations identified in the track-vehicle system. Admissible limits (thresholds) are given for detecting moderate and severe defects using statistical 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 section in moderate and in serious condition was accurately detected.

The thesis is closed with a brief summary in Chapter 9., followed by Chapter 10., presenting new scientifical results, and Chapter 11. presenting the list of publications done within this research.

2. Research methodology

In this research both sides of the condition monitoring are assessed, i.e. analyses have been conducted both regarding the measurements of additional loads in track vehicle interaction and the evaluation of track quality. The research methodology is different for the two sides.

2.1. Track condition monitoring: measurement system and data aquasion

Prior to the evaluation of each track parameter, the recorded data must be synchronized, and some preliminary calibration tests and conversions must be performed for subsequent easier data analysis. In the case of wheel sensors, a further important task is the producing quasi-vertical wheel acceleration from the measured tangent and radial acceleration components.

Synchronization of wheel-mounted sensors

The instrumented vehicle has a rigid axle bogie design, so the sensors - thanks to rigidly fixed wheels to axle - are always in sync. The temporal deviations of starting the sensors have been eliminated by applying a cross-correlation function.

Kinematical model of the running wheel disc

I used a simplified kinematic model of a wheel defined as a rolling rigid body on a horizontal plane, to calculate the quasi-vertical wheel acceleration and the distance travelled. The recorded acceleration data can be decomposed into four independent components: on the one hand there is an acceleration component from translational motion and a sinusoid acceleration signal component caused by the gravity, on the other hand the accelerometer senses the radial- and tangential accelerations (Figure 1.)
Figure 1: Kinematical model of the running wheel: a.) component from the acceleration of gravity; b.) component from translational acceleration; c.) Radial-and tangential acceleration components from rotation

Due to acceleration of gravity $g$, translational acceleration $\ddot{p}$ and the rotational motion, the following acceleration components appear at the measuring axes of "S" sensor placed at $r_s$ radius from wheel center:

\[
\begin{align*}
    a_x &= -g \sin \theta + \dot{p} \cos \theta - r_s \ddot{\theta} + w_x \\
    a_y &= -g \cos \theta - \ddot{p} \sin \theta - r_s \dot{\theta}^2 + w_y
\end{align*}
\]

where $\ddot{p}$ [m/s$^2$] is the translational acceleration of vehicle; $\dot{p}$ [m/s] vehicle velocity; $\theta$ [rad] is the angle of rotation (the reference (zero) position is indicated by the straight line OA on Figure 1); $g$ [m/s$^2$] is the acceleration of gravity; $a_s$ [m/s$^2$] tangential acceleration, $a_y$ [m/s$^2$] radial acceleration; $w_x$ and $w_y$ are the remaining noise component from wheel rail vibration. The above-mentioned acceleration components were determined by using a low-, band- and high-pass Fourth order Butterworth IIR filters. The residual vibration accelerations ($w_x$, $w_y$) on x and y sensing axes are determined by filtering the known component of the recorded signals. These consist of the vibration of the wheel-rail interaction and the impact of forming additional loads too.

2.2. Evaluation of track quality: vibration analysis of vehicle-track interaction

Vibration analysis of the accelerations remaining after filtering the components from the rotation allows the isolation of the vibrations generated by the track defects and the other vibrations resulting from the structural properties of the vehicle, as well as the various types of track defects identification independent from track structures.
Acceleration data recorded on the vehicle-track system, are unsteady, stochastically varying signals in time, thus it is essential to link the frequency domain and time domain information for their vibration diagnostic testing. I used SAWP (Scale Averaged Wavelet Power) [22] and STFT (Short Time Fourier Transformation) in this research among the methods available in the literature. Vibration diagnostic tests were performed using the MATLAB programming family's signal processing toolbox.

The frequency domain characteristics of the vibrations generated by different types of track defects are illustrated in Figure 2, where a measurement example is also presented illustrating the $a_y$ radial acceleration recorded on wheel and the remaining noise component from wheel rail vibration after filtering components of rotation as well as the spectrogram of recorded data calculated by STFT.

The local defects present a “column-wise” appearance in the spectrogram (see spectrogram of Fig. 2c.), since they produce a short time duration impact on the wheel, thus exciting a wide range of frequencies. On the contrary, the second group of track defects appears as a “horizontal” band covering specific frequency ranges depending on the wavelength of track defects and the vehicle velocity (see spectrogram of Fig. 2a. and Fig. 2b.).

From the representation of variable frequency components in time, it is easy to see that when both the frequency range and the time range are examined as small intervals (high resolution), at constant measurement speed, the identification of track types can be identified by separating their frequency components.

After removing the “baseline”, which represents the behaviour of vehicle and the superstructure interaction, the identification of track defects is based on the remaining additional load exceeding the given limits.

The separation of both the "background noise" occurring continuously during the vehicle movement and the periodic or transient type addition loads was accomplished by correcting the baseline of the curve produced by averaging the relevant frequency components of the power spectrum. I applied the method of asymmetric least squares for identifying baseline. The thresholds for identifying track defects were selected based on a statistical evaluation of recorded data of a suitably selected reference line.
Figure 2: The measured characteristic of acceleration waveforms and related frequencies components on different types of track (a) radial acceleration recorded on wheel and the remaining noise component from wheel rail vibration after filtering components of rotation) (a) Rail corrugation: 100-150 Hz; (b) Track irregularity: 0-50 Hz; (c) Rail defect: 0-200 Hz [23]
3. New scientific results

THESIS 1:

I developed a new inertial measurement method (Figure 1.1) for the tramway track condition monitoring, in which the input data for the track quality evaluation are provided by accelerometer sensors fixed to the wheel disc. The results of the developed condition monitoring method depend on both subsystem of vehicle-track interaction, therefore I carried out a calibration process and requirements for controlling the condition of the instrumented vehicle.

Calculation of quasy-vertical wheel acceleration

The resulting vertical acceleration component of the rotating wheel sensors (Q) can be defined with adequate precision as a sum of filtered tangential- and radial wheel acceleration in same angle position, using the form shown by Eq. (1.1):

\[ Q = a_{y,\text{szűrt}} \sin \theta_{\text{angle}} + a_{x,\text{szűrt}} \cos \theta_{\text{angle}}, \]  

(1.1)

where

- \( Q \) – quasy-vertical wheel acceleration
- \( a_{x,\text{szűrt}} \) – high-pass filtered tangential acceleration (0.5 Hz),
- \( a_{y,\text{szűrt}} \) – high-pass filtered radial acceleration (0.5 Hz),
- \( \theta_{\text{angle}} \) – rotation angle of wheel calculated by Eq. (1.2):

\[ \theta_{\text{angle}} = \arctan \left( \frac{a_{gx}}{a_{gy}} \right) \]  

(1.2)

where \( \theta_{\text{angle}} \) the rotation angle (Figure 2.1a.), \( a_{gy} \) gravity component of radial acceleration [g], \( a_{gx} \) gravity component of tangential acceleration [g].

Thesis 1.1:

I verified that on the basis of measurements carried out in consecutive times, with same and different vehicle ends, by comparing the wheel lateral acceleration specified of 0.5 second moving average to the peak to peak distance of \( Q \) the quasi-vertical wheel acceleration deviation specified in the same window width (Figure 1.2 and Figure 1.3) the new measurement setup developed can be repeatedly and reliably applied to track condition monitoring.
Figure 1.1: New experimental set-up: 3-axes accelerometer mounted to wheel disc and its sensing directions

Figure 1.2: Comparison of the recorded wheel accelerations passing with same and opposite ends of vehicle (“A” and “B”).

01. reference measurement (2017.03.31 14:27:14): direction: „A” v = 9 km/h;
06. measurement (2017.03.31 14:28:16): direction: „A” v = 15 km/h;
07. measurement (2017.03.31 14:39:08): direction: „A” v = 15 km/h;
13. measurement (2017.03.31 15:17:58): direction: „B” v = 15 km/h;
15. measurement (2017.03.31 15:29:41): direction: „B” v = 15 km/h;
Figure 1.3: Comparison of measurement directions "A" and "B" with respect to the wheel lateral acceleration compared to the 9 km/h reference measurement

Figure 1.4: Comparison of different travelling directions ("A" and "B") in Kelenföld tram depot

Publication related to Thesis 1: [2], [4], [5], [10], [11], [13]
THESIS 2:

I showed by applying the new measurement setup introduced in Thesis 1 that the accuracy of travelled route (Figure 2.1) calculated from wheel tangential and radial accelerations and actual wheel diameter provides sufficient accuracy (better than 5 m on average tramstop distance) for visually detecting track defects by walking along the line. The degree of accuracy depends on the curves, the wheel diameter and the weather conditions.

![Diagram](image)

2.1. ábra: The calculated travelled route from tangential- and radial wheel acceleration: a.) rotation angle calculated by Eq. (1.2); b.) tangential and radial acceleration recorded on wheel; c.) computed travelled route

Publication related to Thesis 2: [1], [3], [5], [10], [14]
THESIS 3:

For validating the new vehicle dynamic measurement system introduced (Thesis 1) I developed a subjective track condition assessment method and a Geographical Information Systems for identifying and analysing track defects.

As long as there are no sufficient measurement data from vehicle dynamics measurements available (Thesis 1), the developed un-loaded measurement methods can provide an opportunity to verify and validate the data of dynamic measurements.

Thesis 3.1:

I developed a subjective track condition rating system, which independent from track types and in which I have clearly defined the evaluation scales for each aspect, considering my experiences of visual inspection walking along Budapest whole tram network.

The investigated tram line is divided into alignment segments based on its horizontal alignment (straight, circular curve and circular curve with transition curve segments) and the overall track quality of these track segments is assessed separately in each case. Figure 3.1 shows the results of the condition assessments of the investigated line sections with ORTEC RAFS type superstructure in Budapest. The diagrams show the min-, max- and the weighted technical state value of each geometrical segment. Furthermore, the built year and a traffic load are also presented per segments. At the bottom of the diagram the left-, and the right-sided track is separately signed. The * signs the right-sided track within a line section.

Thesis 3.2:

I developed a database structure and an online failure registration form\(^1\) for location-based recording and analysis of track defects observed during walking along the line.

Publication related to Thesis 3: [1], [6], [7], [9], [11]

\(^1\) Online failure registration form: [http://152.66.15.241/Hibabejelento/index.php](http://152.66.15.241/Hibabejelento/index.php)
Figure 3.1: subjective track condition assessment method evaluation example: ORTEC RAFS superstructure type
Figure 4.1: Computed track quality index of alignment segments according to the results of quasi-objective condition assessment:

a.) on right-sided track, b.) on left-sided track;

* significant rail sidewear on curve
THESIS 4:

I developed a quasi-objective track condition assessment method using the data of unladen track geometry measurements, which is independent of the track structures and ensures the automatically evaluation of track quality over segments of track geometry.

TrackScan Track Geometry Meter Device with electro-mechanical sensors is used for the Quasi-objective Track Condition Assessment. About 60 track km are investigated by using TrackScan. This device is suitable for measuring track geometry in unloaded state. Therefore, this method is called partly (quasi) objective condition assessment. The track quality evaluation is based on the defect rate computed separately per track parameters over track segments using the admissible (alarm-, intervention-, immediatly action) limits of geometry measurements.

Publication related to Thesis 4: [6], [9], [11]

THESIS 5:

I developed such automatic detection algorithms for both the rail and the track, which allow the separation of the vibrations generated by the track defects and other vibrations resulting from the structural properties of the vehicle as well as the identification of different types of track defects.

Thesis 5.1:

I verified that the location and intensity of the point-wise “hammering effects” in the different measurement directions can be automatically detected based on the frequency spectrum produced by the scale averaged "Morlet Wavelet" above the given confidence level. In the case of vertical hammering effects, I suggest applying the limit value of $6g^2$ while for transverse direction the $2g^2$.

The local defects present a “column-wise” appearance in the spectrogram since they produce a short time duration impact on the wheel, thus exciting a wide range of frequencies. Therefore, I took full sensing range of the measuring sensors.
Thesis 5.2:

I showed empirically based on extended field measurement and visual observation that the residual vibration acceleration produced by using the BEADS (Baseline Estimation and Denoising with Sparsity²) baseline removal method on STFT or Scale Averaged Wavelet Power spectrum (SAWP), reliably determines the additional loads formed in the vehicle track system regardless of superstructure type.

After removing the “baseline”, which represents the behaviour of vehicle and the superstructure interaction, the identification of track defects is based on the remaining additional load exceeding the given limits.

Thesis 5.3:

Using the baseline correction according to Thesis 5.2, vertical track load measurement number can be determined from the time-localized average of the corrected STFT power spectra of the right and left-hand wheel on the front axle according to the direction of travel using the form shown by Eq (5.1):

$$ F_{ptj} = \frac{\hat{S}_{Q, BE} - \hat{f}_{Q, BE}}{2} + (\hat{S}_{Q, JE} - \hat{f}_{Q, JE}) $$  (5.1)

where

- $F_{ptj}$ vertical track load measurement number;
- $\hat{S}$ frequency-averaged STFT power spectrum;
- $\hat{f}$ estimated baseline using BEADS algorithm;
- $Q, BE; Q, JE$ front left and right quasi-vertical wheel acceleration according to travelling direction.

In the case of vertical track load measurement number, I suggest the use of the intervention limit value of $5g^2$.

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² BEADS MATLAB Tools:
Figure 5.1: Identification of isolated defects using Scale Averaged Wavelet Power (SAWP)
● symbol denotes the location of the identified defects using $1g^2$ limit value for SAWP
I developed a track quality index (denoted in Hungarian DMSZ) reflecting the general quality of tramway track, which is based on the computed area of the region bounded by the graphs of the \((F_{ptj})\) vertical track load measurement number, \((H_{kop})\) the rail corrugation, \((S_{iklB})\) the derailment safety measurement number and \((K_{uk})\) the transversal travel comfort parameters 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. (6.1):

\[
DMSZ_h = \frac{\sum_{h} F_{ptj} + 300 \cdot \sum_{h} S_{iklB} + \sum_{h} K_{uk} + 3 \cdot \sum_{h} H_{kop}}{4},
\]  

(6.1)

where:

- \(DMSZ_h\): Track Quality Index on the current track segment;
- \(h\): length of track segment;
- \(F_{ptj}\): vertical track load measurement number;
- \(S_{iklB}\): derailment safety measurement number;
- \(K_{uk}\): transversal travel comfort (UIC 513);
- \(H_{kop}\): average intensity of left and right rail corrugation Eq. (6.2);

\[
H_{kop} = \frac{H_{kop_{bal}} + H_{kop_{jobb}}}{2},
\]

(6.2)

The track segments in different conditions (poor-, average-, excellent condition) selected by visual inspection along the track (Figure 6.1) can also be distinguished by the distribution functions of the developed new Track Quality Index (Figure 6.2). Furthermore, the half-year later repeated track inspection accurately showed the changes in the deterioration level of the track. I have also showed that the measurements can be replicated at a similar speed and represent the technical condition of the track and its change reliably.

Publication related to Thesis 6: [12], [13], [14]

Developed and validated algorithm based on Zoltán Posgay's basic idea
Figure 6.1: Comparison of measurements recorded before and after reconstruction by DMSZ value on Tram line 51 (h = 6 m).
(h=6 m; V = 25 km/h; * reverse curve and connecting straight section in excellent condition)
Figure 6.2: The distribution functions of the calculated DMSZ on track sections in different condition identified by visual inspection along the track on Tram line 51
Section A: 800 – 1000 m* and 1400 – 1980 m;
Section B: 1000 – 1350 m;
Section C: track section before and after reconstruction, 300 – 800 m.
4. Utilization of the results

The developed *Subjective Track Condition Assessment Method*, the online failure registration form and the constructed database structure enable for track experts to keep up-to-date information about track quality and analyse the recorded defects the modern age appropriate manner.

The *Quasi-Objective Track Condition Assessment Method* for evaluating unladed-track geometry measurements works well in the case of controlling newly-built track alignment, where structural changes and fatigue are not significant. Due to the limitations of the above introduced methods, I developed a new approach based on the vibration analysis of a vehicle-track interaction for tramway track condition monitoring in loaded state.

When I was developing the new track condition monitoring method I had the goal that the developing new parameters based on vibration analysis of wheel-rail contact be matched to the widely used track geometry parameters in order to the recorded track geometry be comparable to the vehicle dynamics measurements.

Regarding the new measurement layout developed, I showed that sensors mounted on the rotating wheel are suitable in the speed range of 15 to 50 km/h used in tramway operation for detecting track irregularities due to the forming addition load caused by the rotating motion. I have also shoved that the measurements can be replicated at a similar speed and represent the track quality and its change reliably.

During the comparative statistical analysis of vehicle dynamics measurements, I showed that the track segments in different conditions (*poor-, average-, excellent condition*) selected by visual inspection along the track can be accurately distinguished by the distribution functions of the developed new Track Quality Index.

The Vehicle Dynamics Measuring System installed on a tram operated by BKV Zrt. was implemented in 2018 according to the new measurement and assessment method presented in this dissertation.
5. Further research

At present, the instrumented tram operates as a special measuring vehicle, so that the system's dependencies can be inspected under controlled conditions (near constant measurement speed, variable vehicle technical condition, impact of different elasticity of superstructures). The disadvantage of dedicated measurements trains is the at least used six-month schedule inspection, which is too long for identifying rapid changes in track quality. 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. After having accumulated enough experience in relation to the dependencies of the developed system, accelerometers fixed to a wheel with a special magnetic solution can provide relatively low cost compared to the modern track-side diagnostic tools, regardless of the vehicle structure, in any types of railway transport systems.

The admissible intervention limits determined for the developed parameters was statistically limited from the low number of measurement data sets available, but their refinement and supplementation with two additional level (alarm- and immediatly action limit) before the final implementation of the measuring system was definitively required. The admissible limits specified in the dissertation are valid only at a measuring speed range of 25 ± 3 km / h, so it is necessary to extend the limits to whole speed range applied in tramway operation or to handle other speed dependency measurements.

In order to design maintenance intervention and to check the effectiveness of interventions, the clarification of the length of track segment and the revision of weighting parameters used within the evaluation of track quality are required by the use of a multi-year measurement data set.

The instrumented tram operated by BKV Zrt will be equipped with a track geometric measurement system so that in the future, with a complex comparative examination of simultaneous recorded track geometry and vehicle dynamics measurements, a new admissible limit system can be developed, which can not only consider the track geometry under load but also the dynamic response of the vehicle.
The new track condition monitoring system introduced in this dissertation, with the addition of a track geometric measurement system, can provide developing a track diagnostics expert system to assist track maintenance professionals in day to day analysis and designing interventions.

When appropriate selecting the parameters of the sensors fixed to the wheel (sampling frequency, sensitivity), it is possible to examine the phenomena of squeal noise in sharp curves. Squeal noise has been a deeply studied problem for many years and extensive literature is now available, but the reason has not yet been clearly clarified. Lubricants used to mitigate the unpleasant effect of squeal noise usually change significantly the braking properties of the vehicles. Sensors fixed to the wheel are suitable for identifying the wheel slip, so they can be used to qualify the lubricants used.

The current standards regarding tramway track geometry design are not supported by the statistical analysis of the kinematic movement characteristics of today's modern vehicles operated in tramway transport. The actual determination of the kinematic movement characteristics of the different types of vehicle is necessary in order to be able to calculate reliably the factors influencing the passenger comfort. The actual kinematic characteristics can be determined by the measurement layout introduced in this dissertation.
6. Publications of the author

6.1. Publications related to the theses


6.2. **Other publications in the field of the research**

7. References in the thesis book:


8. Acknowledgments

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