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COMPARATIVE RIDE COMFORT ANALYSIS OF IN-SERVICE TRAMS ON EXTREME ALIGNMENT CONFIGURATIONS USING SMARTPHONE-BASED SENSING

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Abstract

In this paper, a cost-effective method for monitoring and evaluating the tramway passenger comfort and ride quality are presented using motion sensor data of smartphone fitted to in-service vehicles. Running vehicles experience a broad spectrum of vibrations and oscillations that occur in response to excitation inputs of vehicle-track coupled dynamics. Android mobile platform-based acquisition software is developed (CAFat) for commercial use, and the data from smartphone built-in sensors such as accelerometer and gyroscope are processed by sensor fusion and are coupled with local and global positioning using GNSS data to identify sections with poor ride quality. Results are promising and demonstrate that poor ride quality can be accurately localized on a tramway network. The proposed method enables infrastructure monitoring done by conventional passenger cars and makes the possibility of comparing the ride quality of traditional old-designed and the modular multi-articulated in-service vehicles.

Keywords: tram, smartphone, ride comfort, inertial sensors, track quality

1 Introduction

The railway is a guided transportation system that requires several track inspections and examinations to ensure safe operation. In the design process, the values of the track alignment parameters are chosen to ensure a safe riding with at least a minimum comfort level. A good compromise has to be found between train dynamic performance, maintenance of both the vehicle and track, as well as construction costs.

Tramways overcome horizontal curves with much smaller radii than the conventional railway vehicles, as well as the passengers in a tramway vehicle are more likely to be standing supported or moving around within the vehicle, therefore the risk of passengers losing their balance and falling is increased [1]. The standing passengers in tramway transport can have significant lateral force on entering both the small radius curve and the diverging direction of turnouts depending on the vehicle speed and the structural design of the vehicle running gear. However, the limit values of the lateral passenger comfort parameters (lateral acceleration and its rate of change) are not supported in the present Hungarian regulation [2] by the measured kinematic movement characteristics of the new tramway vehicles operated in Budapest.

The attention of this paper is focused on the measurement of tram irregular movements and vibration using smartphone motion sensors fitted to traditional and modular designed in-service vehicles operated in Budapest tram network. To measure the kinematic motion

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characteristics of these vehicles, an application are developed called “CAFat” in the android software platform that is capable of timing synchronized recording of all phone sensor data and GPS location information. After sensor calibration, the virtual transition length and the representative cross-sections of investigated tramcars were determined in terms of lateral passenger comfort (using the data of yaw-rate gyroscope and lateral acceleration) and then the line tests were carried out only in the relevant vehicle cross-sections. During the kinematic analysis, the lateral accelerations and the yaw-rate gyroscope data recorded on the car body were investigated. The peak values and the main characteristics of the recorded signals were analyzed.

In the next Section, details are given about the measurement setup adopted for experiments, the newly developed android application for data acquisition and the applied data processing methods. Then, Section 3 is intended to face the line test results and gives the main conclusions on the considered possibilities of mobile sensing for tramway track and vehicle condition monitoring.

2 Applied measurement system using mobile phone sensors

2.1 Android mobile-platform based sensor data acquisition (CAFat)

Today’s smartphones include a range of sensing and communication capabilities, in addition to computing which can be used to infer the vehicle kinematics characteristics. We developed an application called “CAFat” running on the Android mobile software platform.

The program (Fig. 1.) has a “Start” button that starts the measurement, which changes to “Stop” after measurement begins. It also shows the time elapsed since the beginning of the measurement and the accuracy of GPS location data. Furthermore, the program allows for the operator to label each event encountered in real-time by pressing a button on the phone screen every time the impact of one class of event was felt.

The synchronized sensor data is logged to a Comma Separated Values (CSV) file. The sensor data in the phone are read out at the maximum possible sampling rate. Depending on the phone model, the available sampling frequency may vary from 100 Hz (for mid-range phones) to 600 Hz (for premium-category phones). To determine the irregular vehicle movements and oscillation, the 100 Hz sampling rate may be already sufficient, because the railcar body oscillations are generally between 0 and 20 Hz, but the investigation of rail surface defects requires higher sampling frequency. Only high-end phones were used in the measurements, whose sampling frequency was more than 400 Hz.

2.2 Measurement setup

The axis arrangement of sensors in smartphones is standardized, independent of the manufacturer. Three-axis accelerometer and gyroscope are suitable for describing spatial motion and the measuring axes follow a right-handed coordinate system. If the phone is positioned horizontally with a display facing upwards so that the charger connector is closer to you, the ‘x’ axis is to the right, the ‘y’ axis along the long side of the phone towards the camera, and ‘z’ the positive direction of the axis points vertically upwards. The positive direction of rotations around these axes is also determined by the right-hand rule. During the measurements, the phone is placed on its long side fixing to the wall of the car body so that the positive direction of the ‘y’ axis is the same as the travel direction (Fig. 1.). In the measuring arrangement used, the axis ‘y’ records the longitudinal acceleration, the axis ‘x’ is the vertical acceleration, while the axis ‘z’ records the lateral acceleration of the car body. The pivoting around the ‘x’ axis is the yaw movement of the vehicle, the movement around ‘y’ axis is rolling, and the pitching movement is around the axis ‘z’. For most of the measurements, the device was attached to the glass of vehicle window using a silicone pad, which arrangement partly filters the higher frequency components, but keeps the low frequencies relating to the irregular oscillatory motion of vehicle.

2.3 Data processing

A) Processing and interpreting acceleration data
The vibration, sudden impact shocks and the orientation in a motionless position can be sensed with accelerometers. The acceleration data measured on the car body is extremely noisy and can not be used directly, prior processing is required. To remove vibrations of higher frequency components that are irrelevant for the kinematic test, a two-way moving average method is applied.

B) Processing and interpreting gyroscope data
The gyroscope is suitable for describing irregular and oscillating movements of the car body. The track alignment and the car body tilt of the train can be derived from the yaw-rate and roll-rate gyroscope data respectively. During measurement, the yaw-rate gyroscope data highly influenced by both the track alignment layout and the design of the vehicle running gear. Therefore, this data accurately describes the steering mechanism of the vehicle on curved track. For each evaluation, a 2 Hz low-pass filter was used uniformly on the raw gyroscope data that complies with the relevant requirements of the EN 12299 standard [3].

C) Relationship between lateral acceleration and yaw-rate gyroscope data
The Fig. 2. compares lateral acceleration and the yaw-rate gyroscope data recorded by Xiaomi Pocophone F1 on tram line 49 in Budapest. The top chart shows the velocity recorded by GPS, the second one introduces the raw (grey-colored graph) and the filtered yaw-rate gyroscope data (black- colored graph), while the third one shows the non-filtered (grey) and filtered (black) lateral accelerations. The measurement was performed on the car body of the Ganz type, articulated tram. The track horizontal alignment can be obtained from the filtered raw acceleration data (using a 0.5 Hz low-pass filter or a moving average with 1.00 s windows width, see the third graph in Fig. 2.), while in the case of the gyroscope, the raw data contains this information.

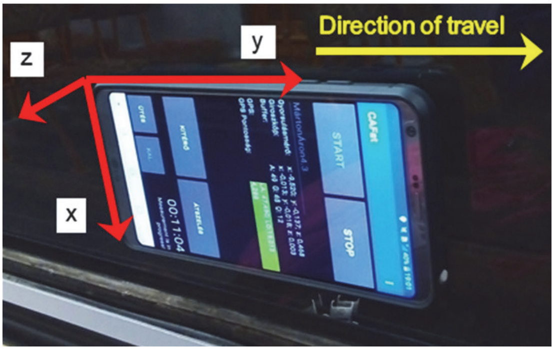

Figure 1 Screenshot of the developed Android smartphone application (“CAFat”) and interpretation of the measurement axes

It is important to mention that when examining vehicles with good running properties, the raw acceleration data also clearly shows the horizontal alignment.

Filtered lateral acceleration and gyroscope data are highly similar (see graphs 2 and 3 in Fig. 2.), which is due to the fact that the data provided by the gyroscope can be used to calculate the quasi-static lateral acceleration using the Eq. (1):

$$a_0 = v \cdot \omega = v \cdot \frac{v}{R} = \frac{v^2}{R} \tag{1}$$

where
a_0 [m/s^2] - quasi-static lateral acceleration,
v [m/s] - velocity,
ω [rad/s] - angular velocity (yaw-rate gyroscope),
R [m] - radius of the curve.

The car body tilting acceleration can be computed by the difference between the filtered lateral acceleration and the calculated quasi-static lateral acceleration. On the section of “Szabadság” bridge (between the position of 3300 and 3600 m) the track is built with 22 mm superelevation. Fig. 2. clearly shows that the yaw-rate gyro is not sensitive to car body roll, while the recorded lateral acceleration contains both the tilting-, and the centrifugal acceleration. The fourth graph on Fig. 2. shows the calculated tilting acceleration compared to the nominal value of track cant measured by TrackScan track geometry measuring trolley (red-colored graph). The reference tilting acceleration is calculated from the measured track cant value.

D) Sensor fusion between magnetometer, accelerometer and the gyroscope data

To calculate device absolute orientation sensor fusion is applied. Generally, the accelerometer and magnetometer outputs include a lot of noise. The gyroscope in the device is more accurate and has a very short response time. Its downside is the dreaded gyro drift, which is accumulated when making the sum of angular velocity to get actual orientation.

To avoid both, gyro drift and noisy orientation, the gyroscope output is applied only for orientation changes in short time intervals, while the accelerometer data is used as support information over long periods of time. This is equivalent to low-pass filtering of the accelerometer and magnetic field sensor signals and high-pass filtering of the gyroscope signals.

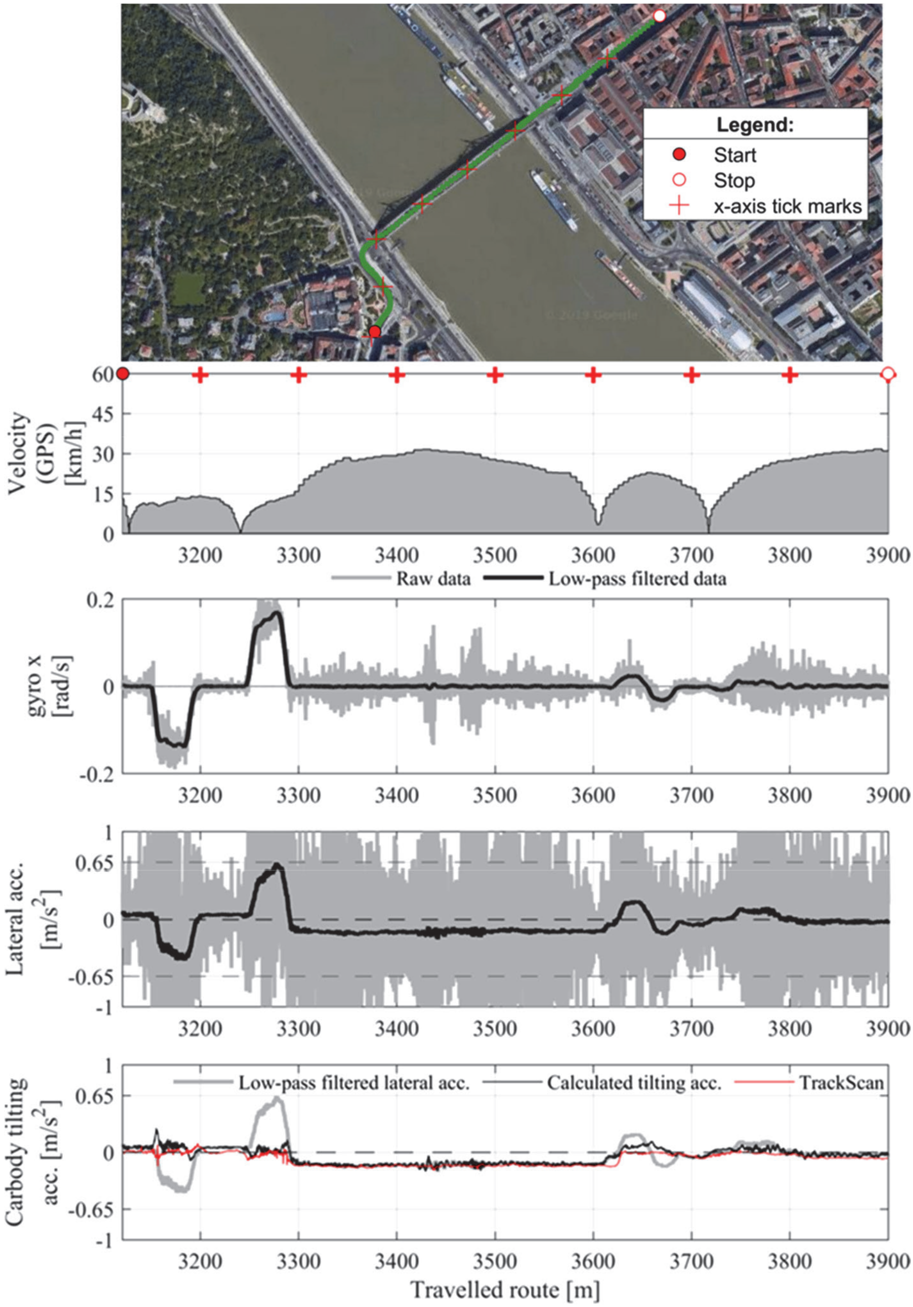

Figure 2 Determining the tilt of the car body using roll-rate gyroscope (gyro_x) and lateral acceleration data of in-service vehicle-mounted smartphone

3 Measurement results

Line test measurements were performed under real traffic conditions with passengers on different classes of tramway vehicles. The current fleet of vehicles operated in Budapest's tram network is not considered homogeneous, apart from standard vehicle configuration, i.e., a car body on two bogies, in modern tram designs various arrangements are applied. The running gear of the modular designed low-floor trams are based on a highly sophisticated axlebridge component and integrated completely into the car body. This structural design produces significant additional stress for the track compared to the traditional bogie vehicles.

The primary purpose of the tests was to determine the ride comfort, therefore the representative position of the passengers was decisive when selecting the measurement location within the vehicles. In determining the critical cross-section, several cross-sections were simultaneously measured on a vehicle and then the line tests were performed only in the determined relevant cross-section.

During the selection of measurement places for line test, the primary consideration was to quantify the extent of irregular vehicle movement (lateral sway and oscillation) and to search for a relationship with the track alignment parameters.

3.1 Curving behavior of investigated tramcars

The virtual transition length of the vehicles was investigated on entering circular curves or on a reverse curve with an intermediate straight section. In the case of abrupt change in curvature, the approximate formulas for determining the lateral acceleration do not take into account the virtual transition length of the vehicle, so curvature function is defined containing both the nominal track alignment parameters and curving behavior of the investigated vehicles. This curvature function must be matching line to the filtered yaw-rate gyroscope data. It is important to note that the value of the virtual transition length determined during the measurements depends greatly on the accuracy of the velocity data, from which the traveled distance was calculated. Nevertheless, the curving behavior of the full vehicle and its parts or modules could be properly separated. The virtual transition length of vehicles validated by measurements is summarized in Table 1.

Table 1 Virtual transition length (d) of tram fleet operated in Budapest

CAF Urbos3 (5 modules)		**Siemens Combino Supra**		**TATRA T5C5**	**TW6000**	**Ganz ICS**
Module	d [m]	Modul	d [m]	d [m]	d [m]	d [m]
C1, C2	1,800	1-6	1,800	6,700	6,400	6,000
S1, S2	6,745					
R2	1,850					

Legend: Wheelbase (italic font); bogie pivot distance (bold font); module length (underline and italic font)

The virtual transition length of traditional bogie vehicles and articulated vehicles equal their pivot distance. However, the curving behavior of modular designed low-floor trams can vary per modules according to the design of their running gear. In the case of Combino tram, each module is supported by axlebridge and its virtual transition length equal to the wheelbase (1,80 m). The CAF vehicle consists of suspended (non-folded) and driven car body parts. The length of the virtual transition that significantly affects the curving behavior varies by vehicle modules: wheelbase distance for driven modules, and module length for suspended ones.

Due to the different virtual transition length, the most sensitive parts of the vehicle are the front and rear modules.

Fig. 3. compares the curving behavior of a conventional bogie and modern low-floor vehicle based on the angular rotation about the vertical axis measured on the car body. The blue-colored diagrams show the low-pass filtered yaw-rate gyroscope data ($gyro_x$) of CAF and TATRA trams respectively, while the black graphs show the defined curvature function, which contains the identified virtual transition lengths of the vehicle or investigated module. In both cases, the measurements are performed at the rear of the trams using Samsung Galaxy S8 mobile phone. The irregular vehicle movement of modular low-floor CAF trams in low-radius curves without transition is evident.

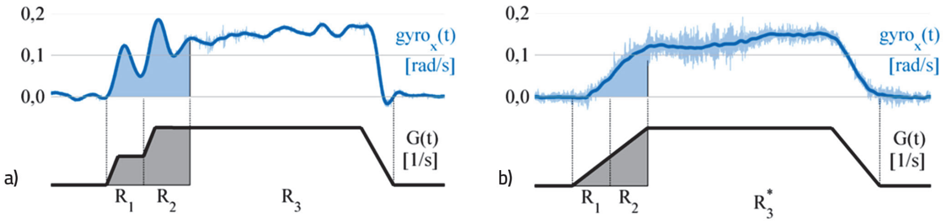

Figure 3 Comparative analysis of a) CAF Urbos3, b. TATRA T5C5 vehicles curving behavior at same velocity on VPh50/25 single track crossing turnout and connecting curved track using yaw-rate gyroscope data of Samsung Galaxy S8 fixed to the rear part of the trams

4 Conclusion

This paper presents measurements of tram kinematic movements and vibration using Smartphone Motion Sensors, as well as qualifies the curving behavior of different classes of tramway vehicles and estimates the vehicle dynamic response on track/rail irregularity.

Smartphones could be mounted basically anywhere on the vehicle to assess ride comfort. The peak oscillatory accelerations recorded at the inside corners of passanger cabin are often significant according to the vehicle structural design, but for qualifying the vehicle curving behaviour the cabin parts close to running gears (bogies) are the most suitable measurement setup.

The performance and sensitivity of sensors in high-end smartphones have significantly improved over the past few years, enabling them to provide useful information to track management due to their reliability and lower cost compared to industrial solutions. The accuracy of the high-end smartphones built-in sensors influenced by many factors (running gear design, track alignment layout, vehicle condition, velocity) and only partially ensure the “mm” precision required for the railways industry, but the real-time measurement of vehicle vibrations during commercial operation allows for rapid response, such as emergency track inspection and maintenance, in situations when vehicle vibration observations detect irregularly large deviations from standard control values. Thus, the use of this monitoring system to perform continuous monitoring of vehicle vibrations allows early detection of deterioration or other track irregularities, thus enabling railway operators to conduct effective maintenance work.

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References

[1] Baasch, B., Roth, M., Havrila, P., Groos, J.C.: Detecting singular track defects by time-frequency signal separation of axle-box acceleration data Detecting singular track defects by time-frequency signal separation of axle-box acceleration data, 2019.

[2] Budapest Public Transport Ltd (BKV), HandBook for design and construction of tramway Tracks, (In Hungaruian) Közúti vasúti pályaépítési és fenntartási műszaki adatok és előírások, Budapest: Budapesti Közlekedési részvénytársaság, 2000.

[3] EN 12299: Railway applications, Ride comfort for passengers, Measurement and evaluation, Brussels, Holland: European Committee for Standardization (CEN), 2009.