

Repeatability of road pavement condition assessment based on three-dimensional analysis of linear accelerations of vehicles

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Abstract. The article provides a discussion concerning a tool used for road pavement condition assessment based on signals of linear accelerations recorded with high sampling frequency for typical vehicles traversing the road network under real-life road traffic conditions. Specific relationships have been established for the sake of road pavement condition assessment, including identification of road sections of poor technical condition. The data thus acquired have been verified with regard to repeatability of estimated road pavement assessment indices. The data make it possible to describe the road network status against an area in which users of the system being developed move. What proves to be crucial in the assessment process is the scope of the data set based on multiple transfers within the road network.

1. Introduction

Up-to-date information about technical condition of road pavement is the key element of the Pavement Management System (PMS). In accordance with the PMS standards, the technical and operating parameters established while road inspections are conducted include load bearing capacity of structures, pavement evenness in both longitudinal and transverse profile, pavement coarseness conditioning anti-slip properties as well as identified and recorded pavement defects. In order to produce a complete description of the state of road infrastructure, it is often required that highly specialised measuring instruments be used. Choosing from among such solutions, one may use mobile laboratories which enable identification and recoding of many technical and operating parameters in a single measuring run. What results from their application in road inspections is the assessment of longitudinal and transverse evenness as well as the said identification and recording of pavement defects [1]. The evenness measurement is conducted on a continuous basis using a laser surface analyser which allows for the results thus obtained to be analysed against a theoretical road profile. This tool ensures highly accurate road cross-section mapping as measurements are performed [2]. The pavement defect identification is mainly based on image processing and recognition technologies. By means of extraction of characteristic features of an image as well as by thresholding, segmentation or morphological transformations of image objects, one can detect the defects and classify them according to pre-assumed dependences of their description [3]. Image processing technologies require ongoing verification of the research material quality, i.e. precision of road mapping in a sequence of images. This, in turn, often leads to the necessity of noise reduction and correction of image defects resulting from the setup of the camera's optical components, but it also requires calibration of the measuring system itself [4]. Application of image processing technologies enables detection and



recording of such defects as bumps, patches, deformations, chipping defects and fractures of various types: longitudinal, transverse, alligator-type and technological cracks [5]. Moreover, test vehicles record the roadway surroundings in a sequence of photographs for purposes of recording and assessment of the condition of individual infrastructure elements in roads' direct vicinity [6,7].

Highly specialised measuring devices are also used to determine anti-slip properties of road pavement. Their operating principle is generally based on measurement of the forces that affect a standard test wheel installed in a test vehicle once the wheel has been set in parallel and at a constant pre-set angle to the direction of motion [8]. A literature review confirms that one can also successfully use visual solutions based on application of light patterns to estimate the level of road pavement coarseness [9]. There are also methods which enable road pavement texture testing by means of calibrated sand [10].

The load bearing capacity of the road structure is typically estimated by the pavement deflection method under pre-set load. Tools which enable such a measurement include Benkelman deflectometers [11] or falling weight deflectometers [12]. However, the latest solution of this kind is the traffic speed deflectometer (TSD) which does not require application of any additional weight (e.g. a concrete slab) to load the road structure, since the thrust applied on the road structure in the process is induced by wheels of a test trailer. Measurements of road pavement displacements due to loading are conducted by means of laser sensors [13]. In order to describe the arrangement of the road's structural courses, and particularly to identify internal voids in the road structure, one can apply a number of solutions based on a ground penetrating radar [14].

Another solution applied to assess the state of road infrastructure is to measure the linear accelerations recorded while the test vehicle is moving. According to the basic approach of this method, a data logger unit records accelerations induced by vibrations of the driven wheel moving on the road subject to examination, while at the same time it is loaded by the mass applied. Paper [15] describes the system architecture proposed, comprising a data collector, a car mounted terminal and a processing system. Field tests of the prototype system were conducted in the Chinese province of Zhejiang. Results of the tests show that, compared to the method of unevenness assessment by means of laser tools, the relative error of the system in question is below 10%, which confirms the accuracy, efficiency and reliability of the solution proposed. What the analysis of road description signals requires is to filter out the noise emerging as an outcome of the vehicle mass system damping. Sample solutions to this problems have been discussed in papers [16] and [17], describing a quarter-car model used in the road unevenness identification process. Paper [18] addresses a case where, in order to determine parameters of the vehicle motion description, drive tests were performed over a portable hump with a known size. The proposed transfer function, established in the process of the half-car model simulation, reflects the vehicle tilt as well as the measuring device installation point. Results of the tests discussed in paper [19] have confirmed the linear dependence of the accelerations recorded (taking average speed into account) on the road pavement unevenness. It has also been proved that data provided by MEMS sensors best describe the magnitude of unevenness in the measuring frequency range from 40 to 50 Hz.

The method described in this article, used for recording and analysis of acceleration signals as well as for implementation of the data processing tool, is referred to as Road Condition Tool (RCT), and it has been devised under the S-mileSys platform being developed as a means to support supply chain links involved in the sector of freight transport. The platform's main goals include efficient transport route planning over the first/last mile by taking the technical condition of the road infrastructure into consideration. The idea behind the system is pursued under the international project entitled "Smart platform to integrate different freight transport means, manage and foster first and last mile in supply chains (S-mile)" under the "Sustainable Logistics and Supply Chains" call within the framework of the ERANET Transport III programme [20]. There are six institutions involved in the project, including businesses and higher technical schools from three countries: Spain, Turkey and Poland. A study concerning acquisition of data for the sake of description and assessment of the road infrastructure condition is the task assigned to the Silesian University of Technology. The assumed concept

underlying the development of the RCT tool stems from a review of the available solutions for identification of road traffic parameters and road pavement condition assessment as well as from analysis of their comprehensiveness and simplicity of the measurement procedure involved.

2. Mobile solutions for acquisition of data on the state of road infrastructure

According to the concept underlying the S-mileSys platform, carriers' vehicles are equipped with mobile devices ensuring connection between the dispatcher at the transport company's headquarters and the driver transporting cargo. Besides the functions typically dedicated to urban freight transport, mobile devices featuring the application in question offer feedback capabilities, such as acquisition of digital data describing the state of road infrastructure. They describe motion dynamics of a vehicle as it traverses the chosen area of the road network. The solution proposed is a mobile device in the form of a tablet or a smartphone running on the Android operating system and featuring the RCT mobile application developed under the S-mile project.

According to the pre-assumed concept, the solution is intended to enable recording of linear accelerations for purposes of identification of the state of road infrastructure. The acceleration data are obtained from a microelectromechanical system (MEMS) and combined with location data obtained from the GPS receiver. The mobile devices to be used must feature both these components as well as a GSM unit. After a part of the route (transport process) is completed, an output file is transmitted from RCT mobile to RCT server via the FTP protocol. Due to communication using different transmission technologies and at different levels of the GSM signal coverage, successful retrieval of data is acknowledged by an ACK signal generated by RCT server. Fig. 1 shows a device with the RCT mobile application installed and running in the manual mode.

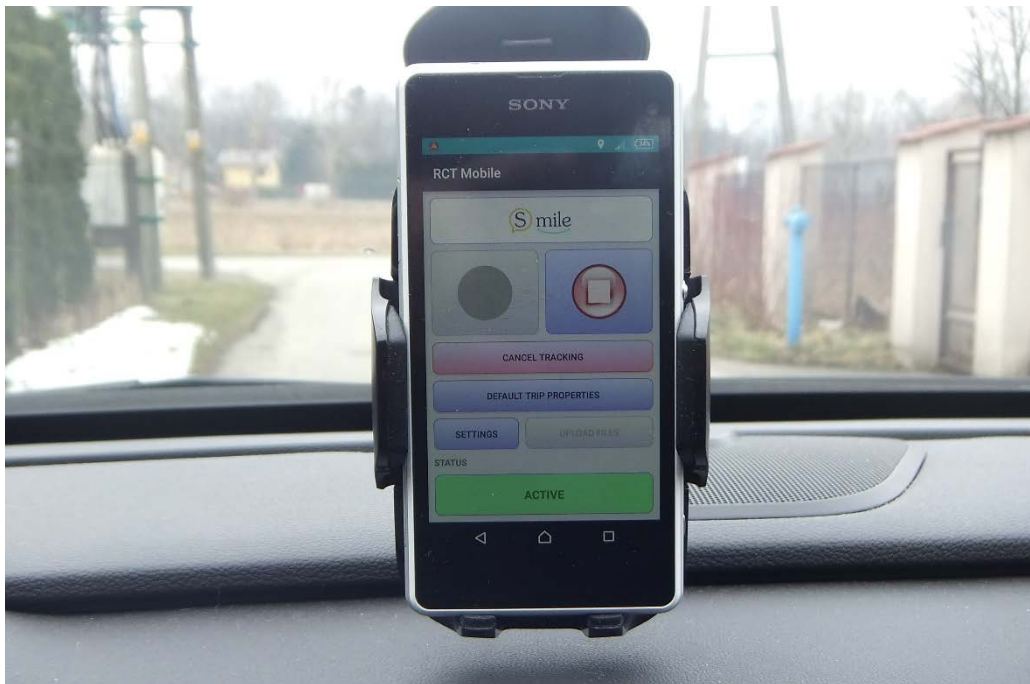


Figure 1. Mobile device with the RCT mobile application installed.

The available graphical user interface comprises six buttons used by the driver and an application status window. Respective functions enable individual application features, including start and stop of the vehicle motion dynamics recording procedure, determining identifiers of the current transport route, setting frequency of data retrieval from the MEMS and GPS modules as well as data recording accuracy.

In the remote operating mode, RCT mobile is handled by Main Mobile Application for Smartphone with the driver being prevented from any interference. The data required for identification of the route, the company and the vehicle as well as the order currently being processed are transferred from S-mile Freightier Tool to Main Mobile Application for Smartphone [20].

An output file is created as a result of measurements, and it consists of two parts. The first part comprises a header with the following parameters that identify the route covered:

- Carrier ID,
- Route ID,
- Vehicle ID,
- Vehicle type,
- Vehicle weight,
- Cargo weight,
- Data acquisition frequency.

The second part is a series of data of the recorded vehicle motion dynamics, including:

- Measurement time stamp,
- GPS geographic coordinates GPS (longitude and latitude),
- Linear accelerations in a three-dimensional system,
- Vehicle speed at the time of measurement.

Below is a sample fragment of an RCT file containing a series of data describing the vehicle motion dynamics.

```
1508043927692;50.265592;19.018385;5.2480;10.1130;-1.6560;92.91;
1508043927704;#;#;-3.7920;9.0210;-3.2840;#;
1508043927713;#;#;4.3380;8.2450;0.4110;#;
1508043927722;#;#;1.0910;9.8540;-3.6770;#;
1508043927731;#;#;-0.9190;10.1610;-4.7500;#;
1508043927741;#;#;3.6680;10.0940;0.3440;#;
```

The # symbol designates the data retrieved from the GPS module. On account of the GSM module's lower frequency of data acquisition compared to the MEMS module as well as the memory occupancy minimisation criterion, data of duplicated values are not repeated. Most typical GPS receivers/modules enable acquisition of data concerning location at the frequency of 1 per second. From the perspective of route mapping, such a record is sufficient. The linear acceleration data retrieved from the MEMS module, on the other hand, can be acquired with the frequency of up to 1,000 per second.

The data recorded in the RCT mobile application file are then sent to RCT server where they are verified in order to check correctness of the data retrieved and filter out irrelevant or failed data. What the server checks is the data series continuity and correctness of the values obtained by analysing affiliation with pre-defined value ranges. In the event of data discontinuity and high deviations of the data recorded from mean values, the filtering procedure is initiated with regard to the given data series. Once the verification procedure is complete, a route recorded as a series of GPS coordinates is converted into a set of the OSM map sections which reflect the actual route. The data conversion proceeds in stages, while the assignment algorithms are based on the following criteria:

- criterion of the GPS track coverage by OSM sections,
- criterion of conformity between directionality of the GPS track and the route of the OSM sections,
- criterion of continuity of mapping of the GPS track against the direction of motion in the OSM sections.

With the foregoing criteria in mind, it is possible to accurately map a vehicle's route recorded as the GPS positions over a set of the OSM sections forming a complete connection between the point of origin and that of the transfer destination. On account of the precision of aggregation of data which

describe vehicle motion dynamics, and consequently also the road infrastructure condition assessment, for the sake of the measurements, a fixed measurement section length has been assumed at 10 m (part).

Aggregated data of linear accelerations, initially subject to filtering and assigned to individual parts of the road network, provide the baseline for estimation of the road pavement condition indices. Such an index assumes a value ranging between 0 and 1, where 0 corresponds to a road part of good technical condition (technical class A as per the applicable guidelines [21]), while 1 defines a section of poor technical condition (technical class D as per the applicable guidelines [21]). For the given road part, the road pavement condition assessment index is estimated in accordance with the following relationship:

$$\delta(d_{id_part}) = [1 + e^{-\beta(d-T)}] \quad (1)$$

where:

d – sum of absolute differences between the recorded linear accelerations (2),

β – parameter defining the function slope, where a high value leads to stepwise behaviour of the function,

T – parameter defining the function shift in a direction that matches value d ,

$$d_{id_part} = \sum_j |a_j^y - a_{j-1}^y| \quad (2)$$

where:

a^y – recorded linear accelerations assigned to the given road part.

Parameters β and T , which determine the function behaviour, were estimated with reference to the linear accelerations recorded in tests of the RCT tool. Their values depended on the category of the given vehicle whose motion dynamics was recorded.

Fig. 2 illustrates the linear acceleration data recorded as well as the results obtained in the road pavement condition assessment for two selected road sections. Section 1 is a road fragment where the surface course of the pavement is on the good condition, while section 2 is a road fragment in poor technical condition.

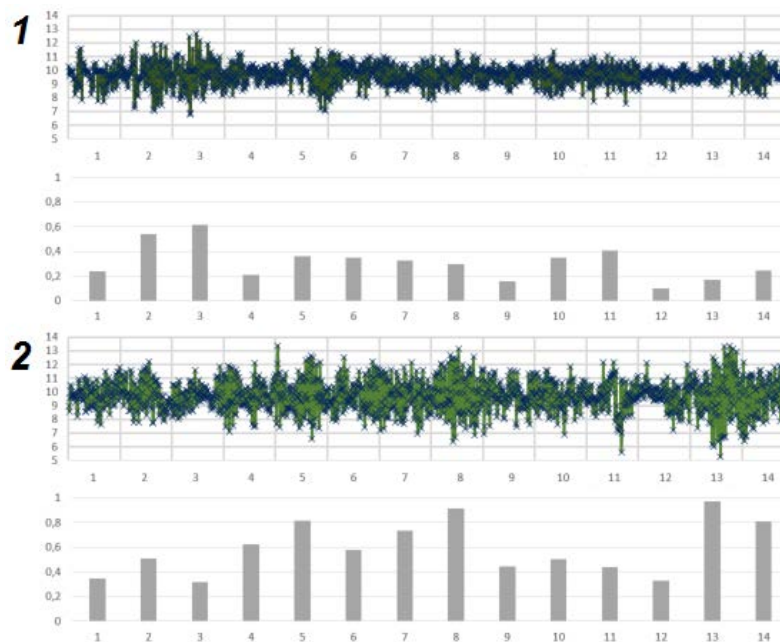


Figure 2. Examples of the road pavement assessment process.

3. Tests of the measurement method proposed

The implemented RCT solution was verified in terms of repeatability of the road pavement assessment indices being established by two kinds of analysis. One of them required tests to be conducted in a pre-set road network fragment by repeated transfers over road parts with a vehicle of specific category and at pre-set constant running speeds. The vehicle used for testing purposes was a passenger car with the RCT mobile data recording tool on board. All measurements were performed by one driver, which was assumed to ensure consistent driving style. Following the measurements, the recorded data of the motion dynamics description were uploaded to RCT server. By extracting road pavement condition indices of individual road parts from the database, it was possible to analyse the repeatability of verified results that described the road infrastructure. Table 1 provides mean values of the pavement condition assessment indices for the selected 10 road parts against specific ranges of the test vehicle driving speed. Both the mean values and the standard deviations have been calculated for all pavement condition assessment indices of respective road parts. The analysis conducted under the study has been illustrated in Fig. 3, where standard deviations of the pavement condition assessment indices have been additionally marked for individual ranges of speed at which measurements were taken.

Table 1. Verification of repeatability of the δ index depending on the vehicle running speed.

Road parts	Mean values of the pavement condition assessment index δ for constant speeds			Mean values of δ index	Standard deviations of δ index
	~20 km/h	~45 km/h	~70 km/h		
1	0.405	0.358	0.399	0.387	0.040
2	0.381	0.437	0.381	0.400	0.062
3	0.410	0.422	0.441	0.424	0.053
4	0.433	0.450	0.514	0.466	0.058
5	0.447	0.492	0.415	0.451	0.057
6	0.481	0.477	0.499	0.486	0.042
7	0.413	0.366	0.449	0.410	0.046
8	0.482	0.468	0.546	0.499	0.071
9	0.450	0.445	0.502	0.466	0.060
10	0.472	0.462	0.407	0.447	0.057

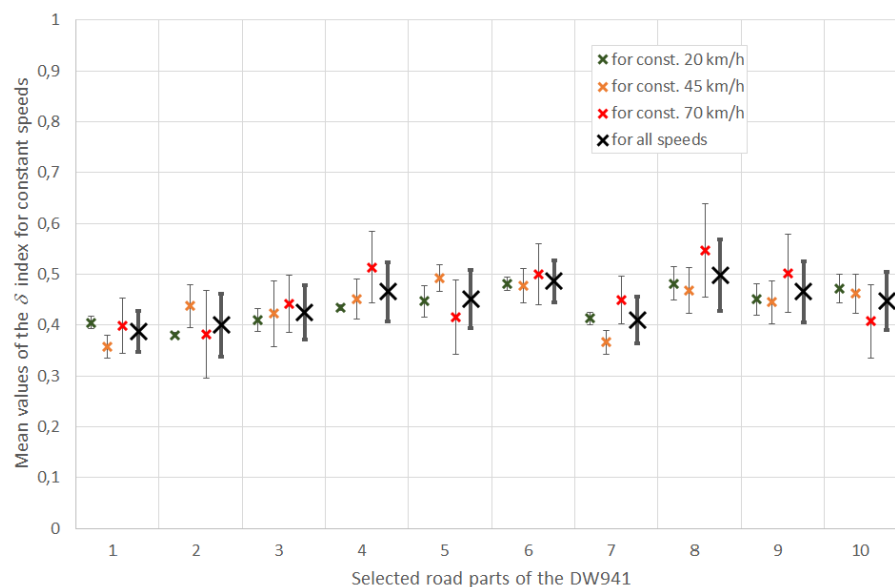


Figure 3. Graphical analysis of the obtained results for constant speeds.

The measurements repeatedly conducted in a 2.12 km long section of the DW941 road, constituting an analysis of 212 road parts, clearly imply that the standard deviation of the road pavement condition assessment indices increased as the test vehicle increased its speed. The highest standard deviation value for the indices analysed came to 0.071. Having assumed a double standard deviation and normal distribution of the values obtained for the road pavement condition assessment indices, one may presume that roughly 95% of the indices being established will display repeatability of values in the range of ± 0.142 .

The second type of the analysis performed consisted in isolating from the database the road pavement condition assessment indices of the given route where measurements were performed by different drivers using vehicles of different categories. The analysis covered transfers made by a passenger car SO, a delivery van SD and heavy goods vehicle SCbP. With regard to the specific design of the vehicle, and particularly its suspension system, an off-road car ST was also isolated from the passenger car category [22]. On account of the driving styles and the recorded running speeds, individual sections of the S52 expressway were chosen for purposes of the analysis, since that is where the smallest speed differences were observed.

Table 2 provides mean values of the pavement condition assessment indices for the selected 10 road parts, as they were established based on transfers made by vehicles of different categories. Fig. 4 provides graphical representation of this analysis.

Table 2. Verification of repeatability of the δ index depending on the vehicle category.

Road parts	Mean values of the pavement condition assessment index δ for vehicles of different categories			
	SO	SD	SCbP	ST
1	0.177	0.133	0.223	0.171
2	0.176	0.179	0.135	0.165
3	0.354	0.393	0.368	0.362
4	0.423	0.428	0.439	0.409
5	0.445	0.493	0.446	0.403
6	0.357	0.354	0.311	0.337
7	0.793	0.770	0.754	0.778
8	0.759	0.757	0.781	0.712
9	0.692	0.739	0.648	0.718
10	0.780	0.816	0.751	0.732

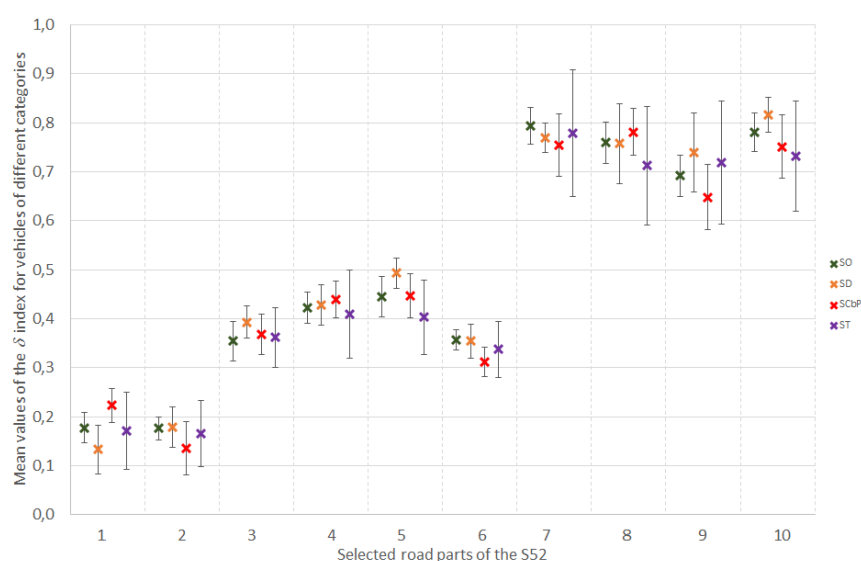


Figure 4. Graphical analysis of the obtained results for vehicles of different categories.

Based on the analysis of the road pavement condition assessment indices established for the S52 expressway section of 14.95 km comprising 1495 road parts, one could observe an increase in the level of standard deviation for the road pavement condition assessment indices established in measurements performed by means of a heavy goods vehicle. For higher values of the road pavement condition assessment index (i.e. road of poor technical condition), the standard deviation observed is higher by 0.087 on the average. For the road section of good technical condition [21], where values of the road pavement condition assessment indices ranged between 0.1 and 0.5, standard deviation values were insignificantly higher, i.e. by 0.043 on the average. In the delivery van and off-road car categories, no considerable change to the standard deviation value of the road pavement condition assessment index was observed.

4. Conclusions

The solution discussed in the paper makes it possible to assess technical condition of road pavement based on the description of vehicle motion dynamics. What proves to be of key importance in this respect is the linear accelerations recorded in a three-dimensional system, associated with the vehicle driving speed at the time of data readout from the MEMS module. Having analysed these data, one can determine specific relationships enabling identification of the current road condition, and once they are correlated with the GPS location – the indices thus obtained can be entered into records.

As discussed in this paper, the verification of repeatability of the assessment indices established has confirmed that analysis of linear acceleration signals can be successfully used to describe the condition of road pavement. The study in question has revealed low correlation between the values of the assessment indices and the speed of test vehicles used to conduct measurements as well as their category. An exception to the foregoing regularity is the category of heavy goods vehicles, which results from the specific design of the shock absorbing system of the driver's cab. Further research is assumed to eliminate this problem.

From the perspective of road infrastructure administration bodies, the solution proposed in the paper may facilitate decision making in the scope of transport system management and road infrastructure maintenance. It provides overall information on the preliminary assessment of technical condition of road pavement in the part of the road network subject to measurements, and enables identification of points in need of immediate or comprehensive repairs.

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