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GPR application – non-destructive technology for verification of thicknesses of newly paved roads in Slovakia

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Abstract

The paper focuses on the use of non-destructive testing technology for measurement of asphalt and unbound pavement structure layer thicknesses for quality control and quality assurance within the context of civil engineering project handover process. In addition to layer thickness information, the pavement roughness was also verified using 3D accelerometer technique and IRI parameters were calculated and analyzed. This presentation summarizes the technology and results of a project where a special section of highway R2 Žiar nad Hronom bypass in the length of 5.2 km was selected for the non-destructive testing. The processing and interpretation consists of extensive data sets presented as longitudinal profiles from survey of each lane of road. The designed layer thicknesses of the road were then compared with measured thickness data. In addition, a comprehensive presentation of the results in GIS view was produced to ensure the subsequent decision-making process easy to execute.
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Keywords: Non-destructive testing; layer thicknesses; quality control; quality assurance; roughness; IRI; GIS;

1. Introduction

During the pavement works and road construction non-destructive testing methods can be used both in quality control (QC) to check afterwards that the pavement/road structure has been built as planned but they can also be used in real time quality assurance (QA). The main techniques presented in this paper are ground penetrating radar (GPR), digital video cameras, laser scanner technique and 3D accelerometers technique. The main benefits of these techniques are that they are non-destructive and they are providing continuous profile over pavement structure in 2D

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and also in 3D, giving 100 % coverage of pavement structure under inspection. Using these techniques, it is possible to identify and measure each road construction layer thickness and its physical properties. Afterwards, these properties can be compared with original road structure design and general paving and road construction norms and guidelines. Accurate and strict quality control using new technologies will enable to confirm that all road structures have been built with the specified design thicknesses, proper compaction and quality of material. Detailed quality control and quality assurance using NDT technologies not only prevents cheating in the industry but also offers opportunity for gaining experience - good quality control survey systems enable contractors to learn from their mistakes, and consequently improve their work practices.

2. Project target

This manuscript focuses on survey results of R2 motorway bypass in Žiar nad Hronom, Slovakia. The survey was carried out in December 2014 by Roadscanners Central Europe, s.r.o. Non-destructive testing technology of ground penetrating radar complemented by 2D laser scanner and 3D accelerometer was applied. The purpose of this survey was to determine the layer thicknesses used in building new road and compare them to the designed structure. Total length of the measured section was 5.2 km. The outputs of the survey includes calculation and interpretation of roughness (accelerometer data), IRI parameters and cross fall (laser scanner and accelerometer data). Results were presented in the form of longitudinal profiles, GIS views and statistical data of each survey line. Data collection was performed on December 4th 2014. Both directions and all lanes of the road section were measured. Total number of surveyed lanes was 4, i.e. 2 survey lanes (slow and fast lane) in each direction. The surveyed section is presented in a map (Fig. 1).

Fig. 1. Situation of surveyed road section.

3. Technology description

Data were collected by Road Doctor Survey Vehicle (RDSV) unit developed by Roadscanners (Fig. 2). This unit collects all data needed for quality control of the pavement. The RDSV unit follows the idea of modern sensor fusion with several sensors measuring different parameters. RDSV system consists of 1) Ground Penetrating Radar (GPR) unit equipped with air-coupled “horn” antenna of 2 GHz frequency to survey dielectric value of asphalt surface and 400 MHz ground-coupled antenna to survey unbound base layers 2) Road Doctor CamLink system allowing digital video data collection during survey 3) 3D accelerometer mounted to the back axle of the vehicle was used to measure pavement roughness, cross fall and IRI values and 4) 2D laser scanner technique mounted on the roof of the vehicle enabled measurement of surface shape, rut depths and ditch depths.

The positioning of all the collected data was ensured by RDSV multiple positioning system with GPS unit, optical encoders and distance measurement unit (DMI). In addition the correct position could be confirmed from the video and laser scanners data (street crossings, etc.).

Fig. 2. Road Doctor Survey Vehicle used in the project data collection. The system consists of 1. GPR system with 2.0 GHz horn antenna and 400 MHz ground coupled antenna, 2. CamLink System for digital video recording, 3. 3D accelerometer and 4. 2D laser scanner.

3.1 Ground Penetrating Radar (GPR)

The ground penetrating radar antenna transmits a short electromagnetic pulse of radio frequency into the medium. When the transmitted wave reaches an electric interface, part of the energy is reflected back while the rest continues its course beyond the interface. The radar system will then measure the time elapsed between wave transmission and reflection. This is repeated at short intervals while the antenna is in motion and the output signal (scan) is displayed consecutively in order to produce a continuous profile of the electric interfaces in the medium (Fig. 3). The profile is shown in grey or color scale, where different shades or colors equal different magnitudes of the reflected amplitudes.

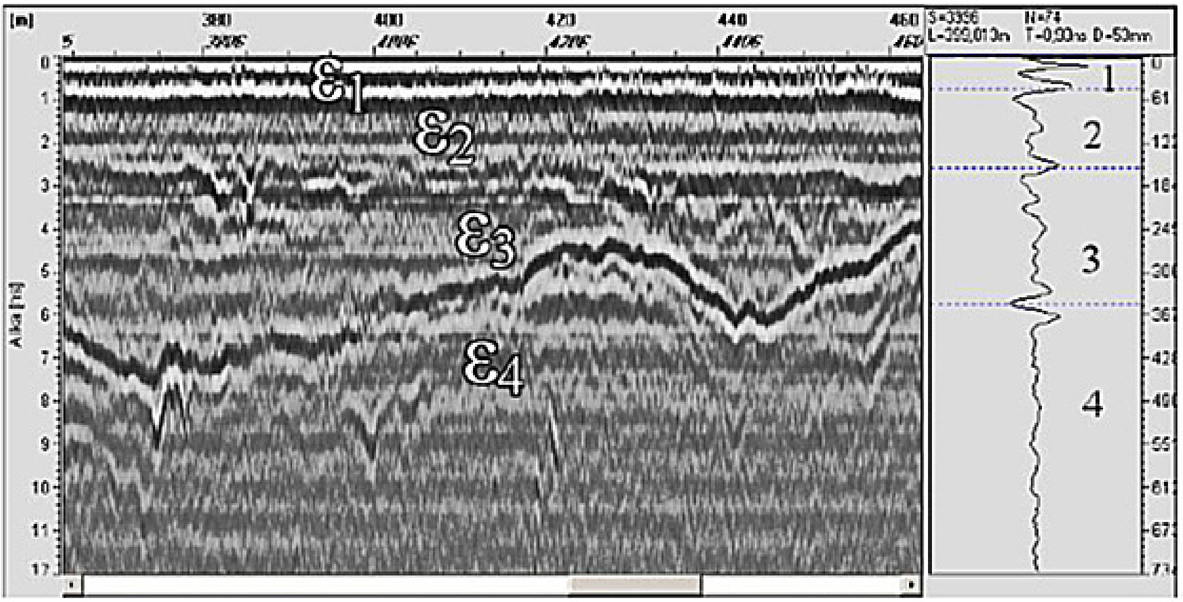

Fig. 3. Ground penetrating radar profile, measured with an air coupled antenna and its individual pulse. The profile has reflections from interfaces of two mediums with different dielectric properties (ε). Image structure's layer 1 describes the pavement, layer 2 describes base course, layer 3 sub-base and layer 4 filter course. The figure shows that the dielectric value of materials (moisture) increases proceeding downwards from the road surface with the exception of the dielectric value of the filter course (ε4), which is less than that of the sub-base and, as such, the polarity of the reflection is inverted (black line in the middle of two white lines).

In general, the propagation speed of the wave and its reflection are normally affected by the dielectric value and electrical conductivity of the medium. They display variability according to aggregate type used in the asphalt, type of binding material (bitumen) and presence of conductive or problem minerals, presence of porosity and fractures, and finally the effect of salt and accumulation of material in the fillings of the pores and fractures. The most important electrical property affecting the GPR signal is dielectric permittivity, which affects the GPR signal velocity in the material.

The antenna wavelength affects the ability of the system to identify objects of different sizes. For example, high frequency antennas with short wavelength have better resolution, but shallow penetration depth, while low frequency antennas with longer wavelength have a coarser resolution, but penetrate deeper into the medium.

The air-coupled systems operate around 1-2 GHz, for this project 2 GHz "horn" antenna was applied. The penetration depth of the horn antennas is limited to approximately 1 m. During the data collection antennas are suspended approximately 0.3-0.5 m above the measured surface. The speed of the measurements is high, even up to 90 km/h. The ground coupled antenna used in this survey operates at 400 MHz. Expected depth penetration is about

3 m. Due to need for a close contact to the surface, the antenna requires lower survey speed, in this case constant speed of 60 km/h. Ground penetrating radar (GPR) data was collected using a GSSI SIR-30 unit with two antennas, 2 GHz air-coupled and 400 MHz ground-coupled antennas (item 1 Fig. 2)

3.2 Road Doctor CamLink System

The CamLink video-logging system was installed on the van roof (item 2 Fig. 2). The GPS device model used for positioning was an APD Communications INCA 2. All of the data was linked to GPS using Road Doctor™ CamLink software. One video camera in a CamLink box was used in the survey in order to record the view of the road.

3.3 3D Accelerometer

Accelerometer is a device that measures acceleration forces (item 3 Fig. 2). Acceleration is the second derivative of position. When a car drives over a road with roughness, the roughness produces accelerations to the car tire. Bigger amplitude and shorter wavelength of the roughness produces larger acceleration. In other words, severe damages of the road produce large accelerations. Together with GPS-positioning system the measured accelerations can be positioned on the road. The accelerations also depend of the driving speed, so a constant driving speed on the whole section is desirable. Acceleration measurements were carried out using Xsens MTi-G accelerometer and integrated GPS-receiver. The accelerometer was attached to the back axle next to the right tire, so that the suspension of the car does not affect the measured accelerations. During the measurements MTi-G measured accelerations at a frequency of 100 Hz (100 times per second). A constant driving speed of 60 km/h was pursued in order to achieve the best possible data quality.

The data analysis was carried out using Road Doctor™ software. The acceleration data was linked to the survey line and analyzed together with other road survey data.

3.4 2D Laser Scanner

Laser scanning is a technique where the distance measurement is calculated from the travel time of a laser beam from the laser scanner to the target and back. When the laser beam angle is known, it is possible to determine road cross sections, and when the car position is known, it is possible to make a surface image from the road and its surroundings. Laser scanner also measures the remission (or intensity) of the reflected laser beam, which helps in detecting different materials and structures on the road, because the intensity of the reflected beam is different for different materials such as road paintings, patches and old or new pavement.

In this project the data collection was carried out using a SICK LMS151 laser scanner (item 4 Fig. 2). The laser scanner was mounted to the back of the survey van.

4. Data processing

The GPR data was processed and interpreted in Road Doctor Pro® software. The digital video, laser scanner and accelerometer data were imported into Road Doctor Pro® for integrated interpretation and analysis. The GPR interpretation carried out mainly follows the most important interfaces for this survey; the interfaces of layers which should be present according to design plans. Exception was the first two layers: the first 40 mm layer of “Asphalt mastic blacktop” could not be interpreted separately. So the first two layers were interpreted together, the first interpreted layer interface locates approximately in the depth of 100 mm. Interpreted layer thicknesses were compared to designed structures.

Accelerometer/gyroscope data was processed and analyzed in Road Doctor Pro® software. 10 m IRI values were calculated from the Pitch values of the gyroscope. These values describe the longitudinal roughness of road surface.

Vertical acceleration (AccZ) values are also shown in the results, which give more information about longitudinal roughness. Cross fall values were measured by the gyroscope.

Laser scanner data was processed and analyzed in Road Doctor Pro® software. Remission (reflectivity) data gives good visual information about road paintings and other objects in the road area. Elevation values were analyzed in different ways using the Road Doctor Pro® software. Ditch depths and 10 m average rutting were calculated from the data. Point heights from road surface are presented in colors in the elevation views, together with laser cross sections.

4.1 IRI calculation method

The device measures the vertical and horizontal acceleration, roll, pitch, yaw and GPS-location. The IRI-calculation algorithm uses pitch value, which measures the longitudinal angle of the device and the van. The angle is measured 100 or 200 times per second. The accurate distance along the measuring line is measured using GPS or odometer. The road profile is calculated using summing the change in elevation at each measuring point.

The change in elevation is:

$$dZ_n = \tan(pitch_n) * (D_n - D_{n-1}) \quad (1)$$

where

D_{n-1} = Distance at location n-1
D_n = Distance at location n
$pitch_n$ = Pitch value at location n

The elevation at location n is:

$$Z_n = Sum(dZ_j) \quad (2)$$

j = 1 to n

The profile is resampled to 0,25 meter point interval and filtered using 100m high-pass 3rd order Butterworth filter to remove the longest wavelengths and possible bias, as described in the IRI-definition. The resampled and filtered profile is used to calculate the IRI value for each of the points. The formulas are the same as the formulas published in the book: WORLD BANK TECHNICAL PAPER NUMBER 46, Guidelines for Conducting and Calibrating Road Roughness Measurements, 1986, by Michael W. Sayers, Thomas D. Gillespie, and William D. O. Paterson [1]. The measured IRI-values are used to calculate the required distance average of 5 m, 10 m, 20 m, 100 m, etc. The measured IRI results have been compared to the values measured using standard profilometer. Comparisons have been made in Finland (fig. 4) and also in Azerbaijan. The correlation was good. The method is especially suitable for gravel roads and very poor condition roads, where laser and accelerometer based profilometers could fail or malfunction. The method also allows speed variation from 0 km/ up to 60 km/h. After that the speed starts to affect the pitch values considerably dampening the higher IRI-values.

The results from Roadscanners' RD LS-3DAcc system and standard profilometer system, were correlated in network level measurements in Azerbaijan. The features were well defined but the value levels were shifted. The levels were matched using a correction formula:

$IRI = (1.335 * IRI_{roadscanners}) + 1.1408$

After using the correction the R^2 was 0,807.

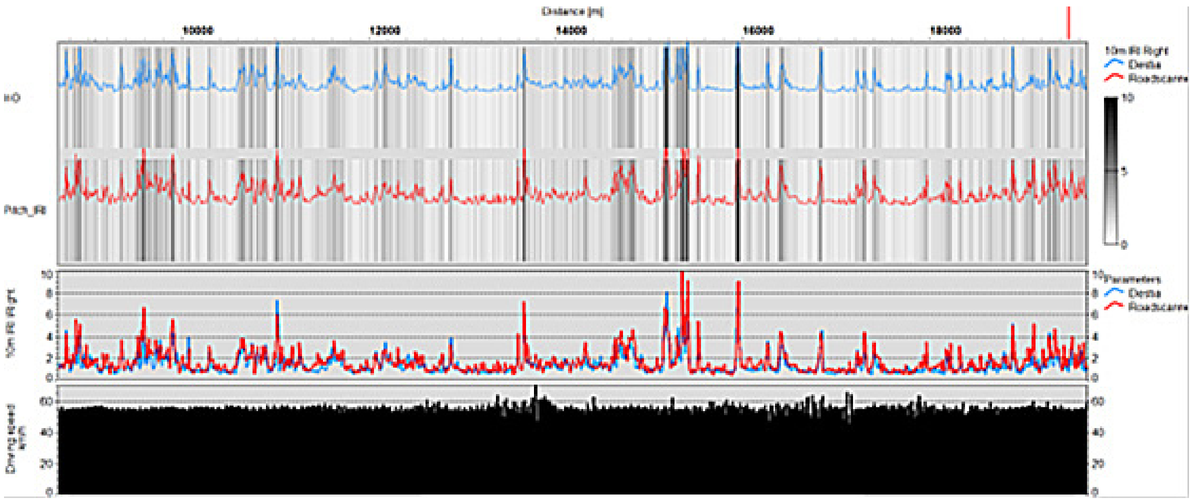

Fig. 4. IRI values measured using standard profilometer and Roadscanners' Pitch method (In Finland).

4.2 Rutting calculation method

The rutting is measured in RD LS-3DAcc-system using a laser scanner, which scans the road surface in cross-section direction. The scanning density is 0,6667 degrees and scanning frequency 100 Hz respectively. The typical grid size is 3 cm x 17 cm at 60 km/h and at 3 m scanner elevation. Thus for each 3.2 m wide scan sub-section there are 85 points. The statistical error for each laser scanner point separately is 7mm, but after taking average of 10 cm x100 cm i.e. 17 points the error decreases to 1,7 mm. While the actual output is provided as an average value of 5, 10, 20, or 100 meters the error is decreased down to 0.76 mm, 0.54 mm, 0.38 and 0.17 mm. This accuracy is adequate for most purposes. The operator can define the calculation width, but usually 3.2 m width is used. The left, right, and maximum rutting value and ridge value can be defined using standard string method. The software includes also algorithms to calculate the rutting using the cutting edge and two bars method. The outliners can be also removed in the calculation to make the errors smaller. The system measures also the reflectivity map of the road surface, which makes possible to monitor the van location compared to centerline or lane marking. One issue causing errors in rutting calculations and comparison of the results from year to year is varying driving path. The recorded driving path makes possible to match the calculation areas and make the results more valid for comparison.

5. Project results

5.1 GPR profile

Interpretation of data collected by 2GHz air-coupled antenna between km 5,4 – 5,9 in continuous profile in slow lane (upper window) and fast lane (lower window). Although there were data collected by ground coupled antenna also, in regards to the project target it was not necessary to interpret them.

Fig. 5 shows comparison of interpreted layers of the road structure from GPR (measured thickness shown as continuous line) with project design thickness (shown in different color columns for each layer) in slow lane (upper window) and fast lane (lower window). Example of comparison result (red circle) - Designed structure of the last layer was up to depth of 0,6 m while measured structure almost reached the depth of 0,8 m. In this place, constructor used more material than the amount stated in project design.

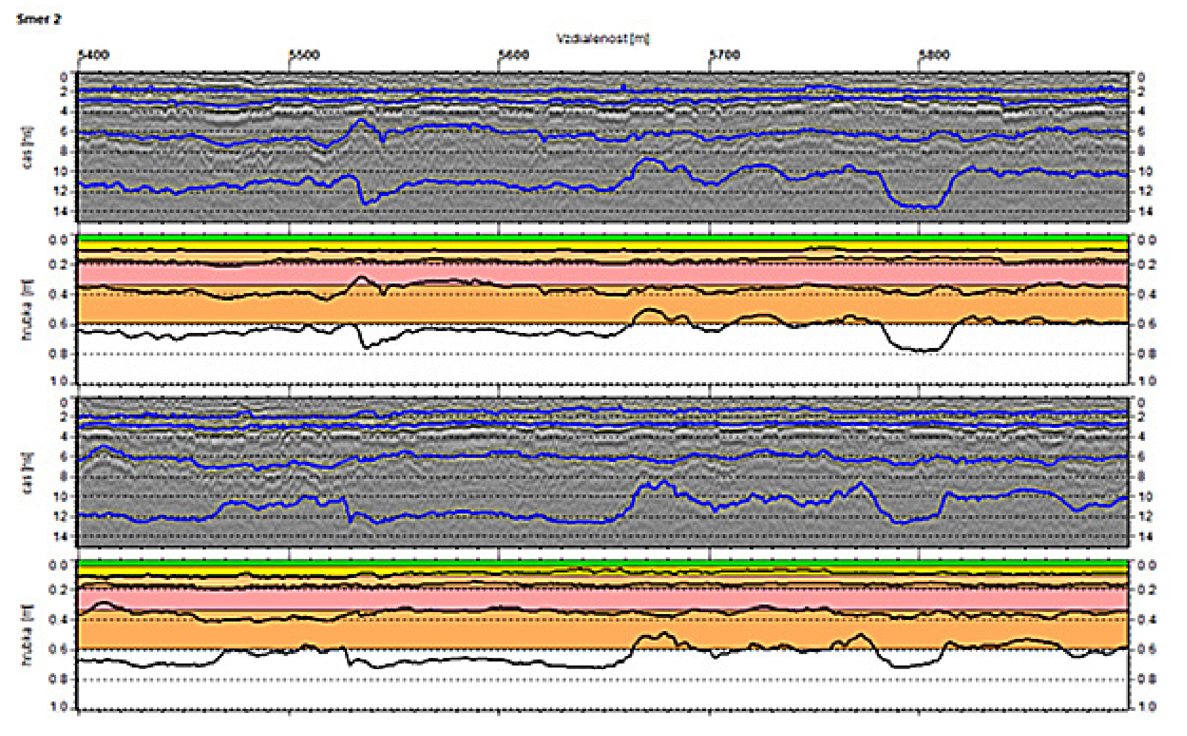

Fig. 5. Window 1 and 3: GPR interpretation of 2GHz ground coupled antenna, slow and fast lane, direction 2. Window 2 and 4: Comparison of measured layer thicknesses (shown as continuous line) with project design (different column color for each layer). Red circle: Example of comparison - Designed structure was up to depth of 0,6 m, measured structure was almost to the depth of 0,8 m.

5.2 Layer thicknesses

The layer thicknesses were also reviewed statistically. The εr value typical for each material was used for each layer in calculations of thicknesses. In the statistical evaluation the results of each layer thicknesses were categorized into 3 groups while each is represented by different color in the map view.

Statistical analysis show that in average 24,5 % of all layers are built thinner than 10 % of designed structure. In average 35,1 % of all layers are between ±10 % compared to the designed layer thicknesses. In average 39,3 % of all layers are thicker than 10 % compared to the designed thicknesses (fig. 6). It should be noted that assumption in the calculations was that bridges should also have 100 mm asphalt layer. All other layers have not been interpreted on the bridges.

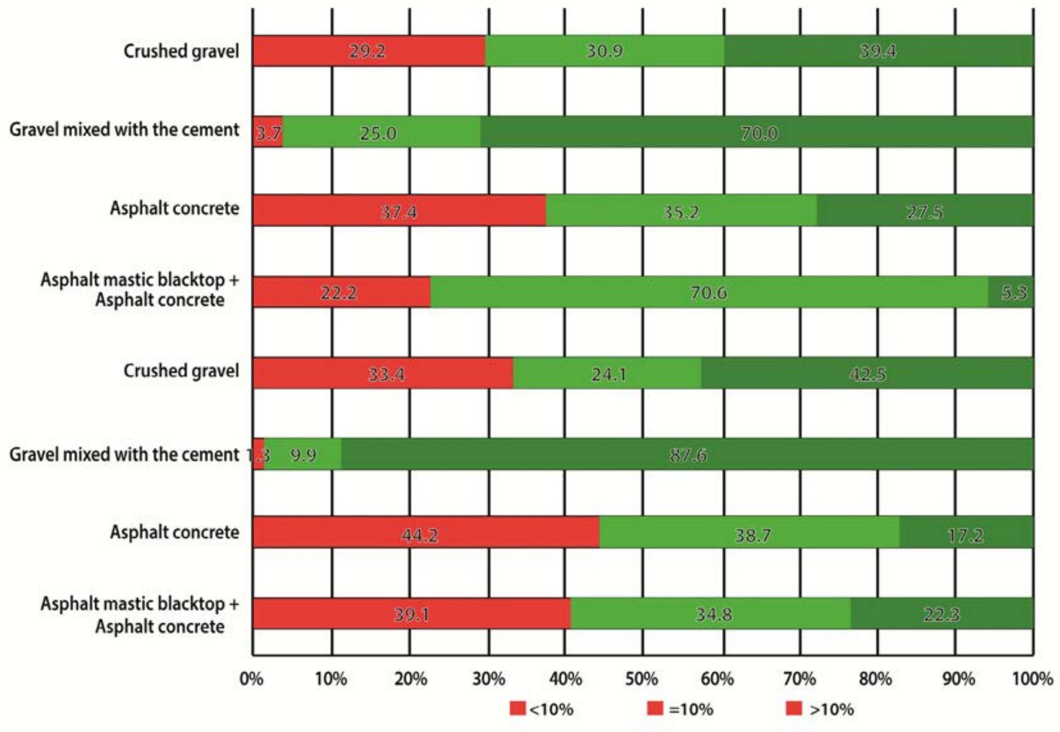

Fig. 6. Statistical analysis of layer thickness according to group (color) categorization, both lanes, direction 2.

Based on analysis, the average of measured thicknesses of each layer met quite well the thicknesses in project design. Asphalt mastic blacktop + Asphalt concrete-layer (interpreted as one layer) is slightly less than designed in direction 1 slow and direction 2 slow and fast lanes. Asphalt concrete layer is slightly less in all lanes. The last two layers (Gravel mixed with the cement and crushed gravel) are in average thicker than designed. Table 1. Presents detailed average values. Fig. 7 presents the results in a form of GIS map.

Table 1. Average values of layer thicknesses in slow and fast lane, both directions.

	Layer 1	Layer 2	Layer 3	Layer 4
Project design values	0.1	0.08	0.15	0.26
GPR values, direction 1, slow lane	0.097	0.079	0.175	0.279
GPR values, direction 1, fast lane	0.101	0.076	0.174	0.276
GPR values, direction 2, slow lane	0.098	0.078	0.179	0.266
GPR values, direction 2, fast lane	0.098	0.074	0.189	0.269

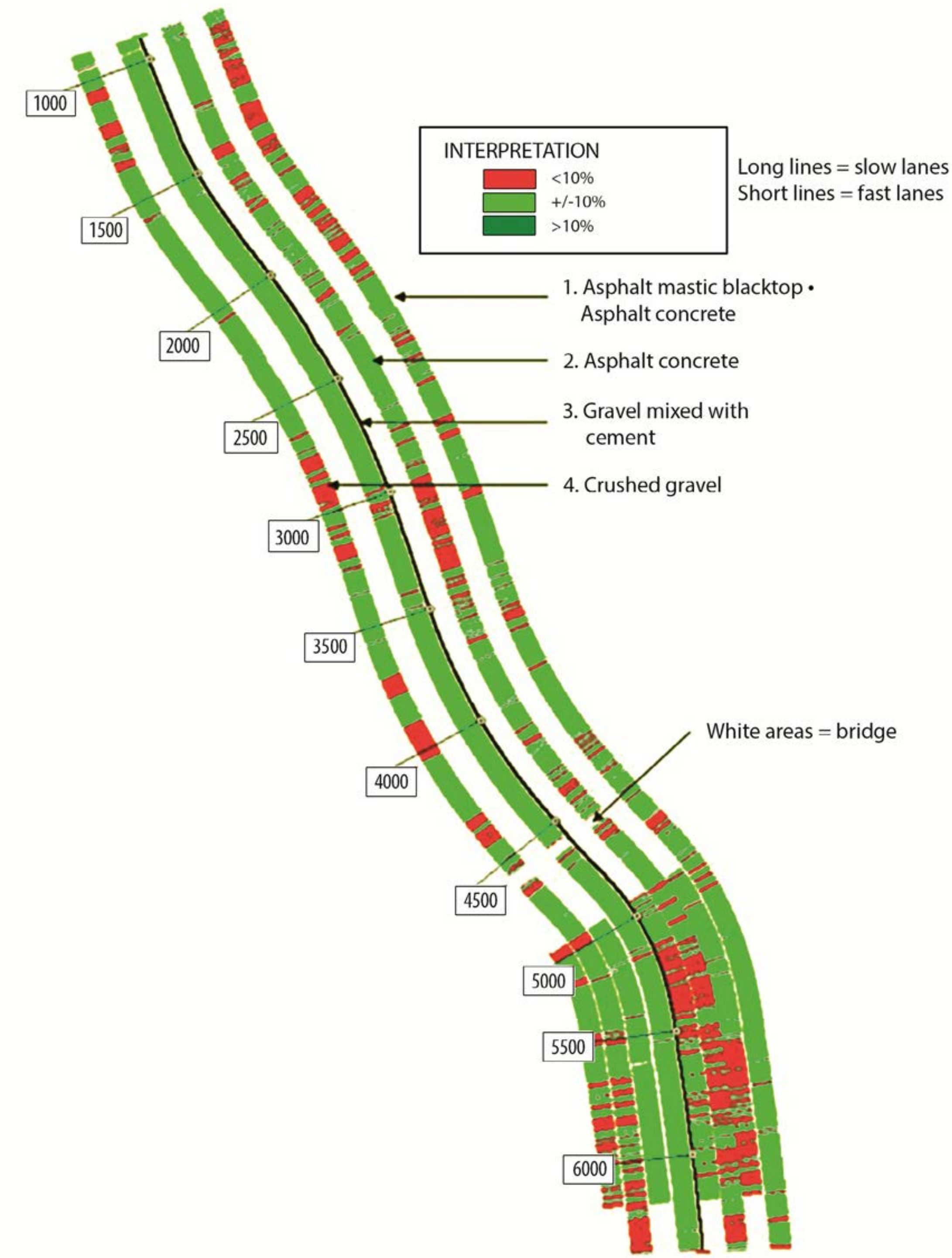

Fig. 7. Interpretation of layer thickness in map view.

5.3 IRI 10 m

10m IRI and vertical acceleration values were reviewed from accelerometer and gyroscope data. The road surface appears mostly even. The highest values were caused by bridges and especially their construction joints, some minor peaks were also caused by pavement joints. One reason for some minor unevenness could be dirt on the road that was visible during measurement (Fig. 8).

Table 2. Average values of IRI in slow and fast lane direction 1 and 2

IRI	Direction 1 slow lane	Direction 1 fast lane	Direction 2 slow lane	Direction 2 fast lane
	1.05	1.37	1.03	1.00

a b

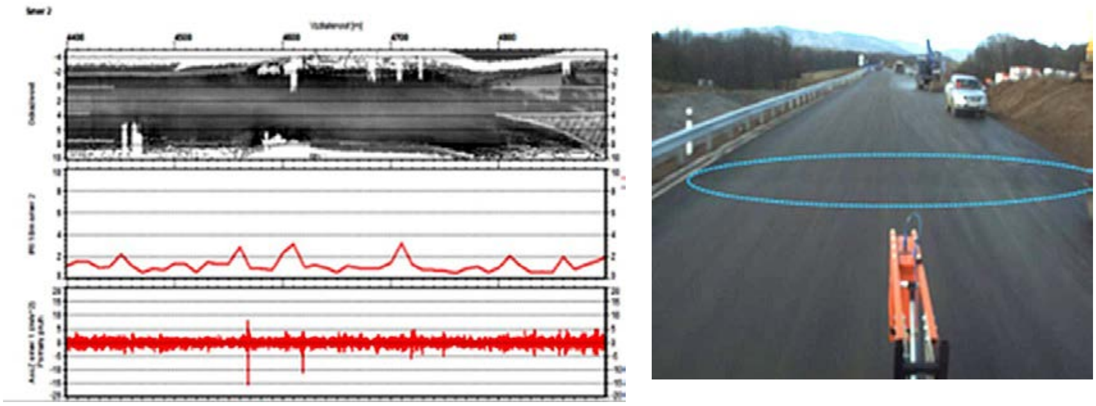

Fig. 8. Minor peak in IRI 10 m value caused by pavement joint, slow lane, direction 2

5.4 Cross fall and ditch depth

Despite the cross fall measurements were disturbed by cars and construction machines blocking the driving path in many places (in these places the measurements do not show the correct value), in places where the survey car could drive normally on the lane, cross fall values seem to be very close to the designed cross fall. Shape of the road cross sections and slopes looks to be good. Ditch depths were calculated and are shown as a map (Fig. 9).

a b

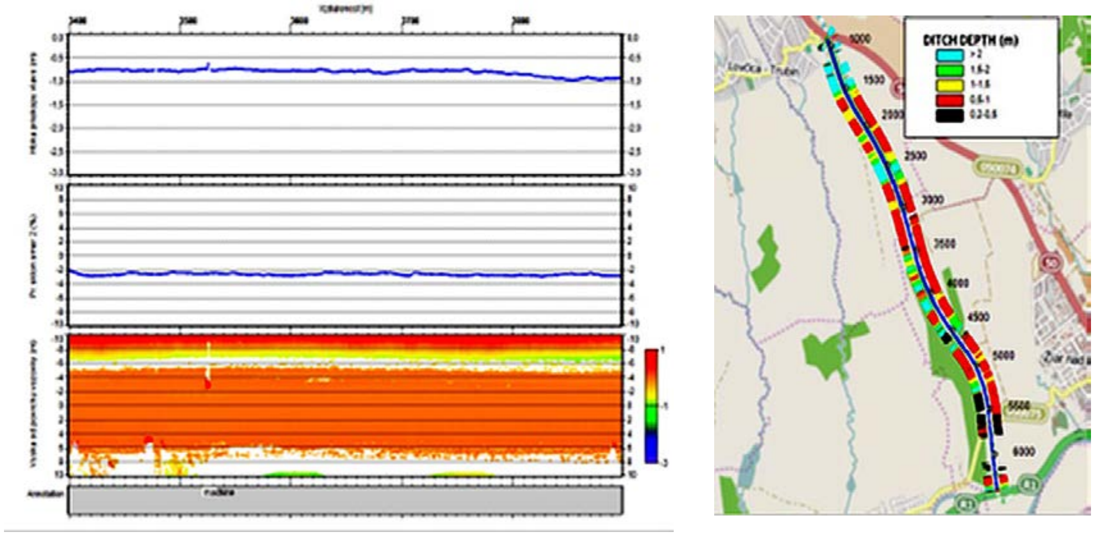

Fig. 9. Interpretation of ditch depth, cross fall and heights in direction 2. Ditch depth shown as a map.

5.5 Rutting

Despite the rutting measurements were also disturbed by cars and construction machines blocking the driving path in many places (in these places the rutting measurements show higher value than actual), in places where the survey vehicle could drive normally on the lane, rutting values are generally quite low.

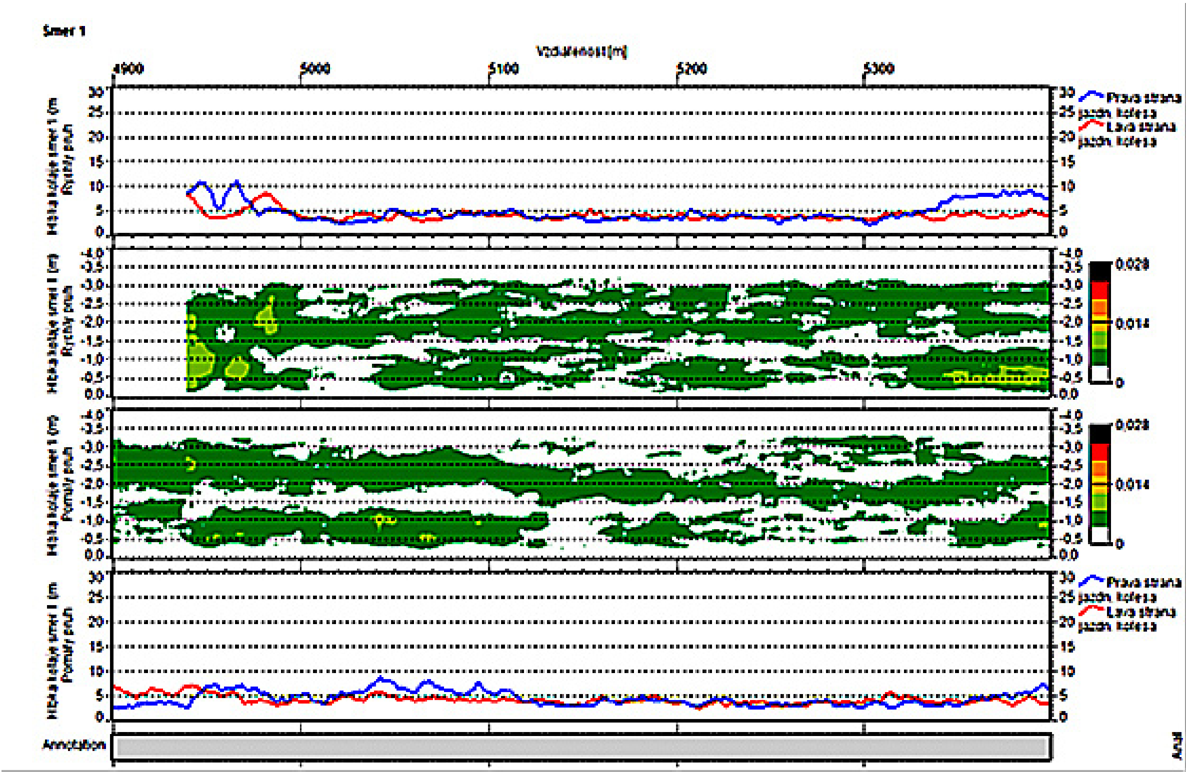

Fig. 10. Interpretation of rut depths in direction 1, slow and fast lane

6. Conclusion

The aim of this project was to evaluate the quality of construction of road R2 in Ziar nad Hronom based on data collected by GPR, 2D laser scanner and 3D accelerometer. Furthermore, the measured values were later compared with the project design provided by contractor. Results from statistical analysis showed that the measured layer thicknesses (actual situation) match the designed thicknesses. Layer thicknesses fulfilled the designed structure thicknesses in a satisfactory manner. Approximately ¼ of all layers were built by more than 10 % thinner than designed structure. Major part of all layers were built by more than 10 % thicker than designed. In average 35 % of all layers were between ±10 % in comparison to designed thickness.

Data acquired by 2D laser scanner and 3D accelerometer were disturbed by cars and construction machines parked on the road during measurement, however in places where they did not disturb the measurement, results proved to be quite good. According to the accelerometer data there are only some very minor longitudinal unevennesses on road´s surface. In accordance with laser scanner data, the road is pretty smooth in transverse direction.

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