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ACQUIRING ROAD PROFILES USING WALKING-PROFILER AND COMPUTER MODELLING PLANOGRAPH'S MEASUREMENT

POZYSKANIE PROFILU DROGI Z UŻYCIEM *WALKING-PROFILERA*, A NASTĘPNIE KOMPUTEROWE ZAMODELOWANIE RZECZYWISTEGO POMIARU PLANOGRAFEM

Abstract

The assessment of road pavements in terms of their properties and surface features is both complex and difficult. The indicators which describe the surface quality are eg. a longitudinal and transverse profile, a coefficient of friction, the International Roughness Index (IRI) and surface cracks. The article presents a method of using the data describing a real longitudinal profile of pavements, which was obtained by way of a self-constructed device named Walking-Profiler. It also proposes a way of calculating it with the use of numerical modelling of a Planograph, and also (simultaneously) the collected data can be used to calculate the International Roughness Index.

Keywords: *IRI, Walking-Profiler, Planograph, Planograph Simulator*

Streszczenie

Analiza nawierzchni drogowych pod względem ich parametrów i cech powierzchniowych jest złożona i kłopotliwa. Czynnikami, które charakteryzują jej jakość powierzchniową, są m.in. równość podłużna i poprzeczna, stan spękań, wsp. tarcia, IRI. Artykuł prezentuje propozycję wykorzystania danych opisujących rzeczywisty profil podłużny nawierzchni jezdni, zebrany przy zastosowaniu własnej konstrukcji urządzenia profilometrycznego oraz przeliczenia ich przy użyciu numerycznego zamodelowania planografu, a także (niejako przy okazji) zebrane dane mogą posłużyć do kalkulacji wskaźnika IRI.

Słowa kluczowe: *Wskaźnik IRI, Walking-Profiler, Planograf, Symulator Planografu*

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1. Introduction

Road surface profile measurement is a compulsory stage during the construction of roads and highways; they are the final stage. Without receiving the optimum measurement results, the road may not be approved for use. If the test results do not meet the requirements of the profile referred to in RMTiGM Dz.U. 1999.43.430 [1] or RMTiGM Dz.U. 2002.12.116 [2], the commissioning of road surface by the customer may be impossible or financial penalties will be imposed on the Contractor for failure to comply with the desired quality of the construction work. Longitudinal and transverse profile measurements are also performed periodically on networks of roads administered by different levels of road administration, i.e. the General Directorate for National Roads and Motorways (*Generalna Dyrekcja Dróg Krajowych i Autostrad – GDDKiA*), Voivodship Road Authorities (*Zarządy Dróg Wojewódzkich – ZDW) or Local Road Authorities (Zarządy Dróg Powiatowych – ZDP*), in order to determine the degree of road consumption and, if necessary, to make structural corrections or surface treatments in homogeneous road sections, for which test results do not meet the requirements contained in the relevant reference documents (The Pavement Condition Evaluation System – *System Oceny Stanu Nawierzchni – SOSN*). In Poland, since 1969, that is since the time of the introduction of the standard BN-68/8931-04 [3], the methods of measurement described in this norm have been applied and measuring equipment is still developed on the basis of schemas described in the standard. Longitudinal profile measurements with the use of the so called: method of ‘patches and wedge’ are quite rare, but measurements with the use of a planograph are very often applied in a measurements procedure. However, the use of the planograph is problematic because of its design, size and weight and also the way of carrying out the measurements. It was, therefore, necessary to develop a better method, which, as far as possible, would completely displace a planograph, at the same time obtaining identical measurements results.

This article describes the project, whose goal was to build our own profilometric device, hereinafter referred to as ‘Walking-Profiler’, which allows for registering the real pavement longitudinal profile. The next step was to design and create software using numerical methods, the aim of which was to correctly model (visualize in a computer program) and calculate the reaction of a planograph moving on a precisely registered longitudinal profile of the test section of the road. Having the data of the real road profile, the International Roughness Index (IRI) can also be determined, which is one of the indicators that describe the quality of the pavement.

2. International Roughness Index (IRI)

IRI – the International Roughness Index is a parameter describing the work of the vehicle suspension in the ‘top-down’ axis for a hypothetically perfect car vehicle, the so-called ‘golden car’ [6], moving at a constant speed of 80 km/h along a registered road pavement profile on the specified road section. This coefficient is expressed in mm/m (for short road sections) or in m/km (for long road sections). In accordance with the Polish classification system of roads – the so called SOSN (The Pavement Condition Evaluation System – Polish: System Oceny Stanu Nawierzchni – SOSN) the tested road section needs to be divided into

50- or 100-meter-long sections (50-meter-long road sections are required at the stage of road pavement commissioning, 100-meter-long sections are required for periodic road check-ups) and IRI indices are determined for each of the sections.

For new roads, the obtained results need to be arranged in the increasing sequence, and it is necessary to determine values congruent with quantiles: 0.5; 0.8 and the maximum value, and then make a comparison of the obtained profile parameters with the extreme values (requirements) determined in appropriate documents [1, 2]. If the index exceeds the permitted norm, it must be stated that the whole tested section does not meet the requirements, and thus cannot be accepted for use. In some situations, such a section may be accepted for use, on the condition that structural defects do not pose a danger for users, and these defects do not have a significant impact on the deterioration of the technical condition of the road. A customer may reach an agreement with the contractor by forcing them to extend the warranty period or reducethe contract price.

As far as conditions permit, the road pavement needs to be repaired (IRI values for individual sections of 50 or 100 meters indicate the points which must be repaired). For older regularly used roads on which periodic tests are carried out, it is necessary to mark the places which require an immediate general repair (IRI outside the norm) on the basis of the table of results, the short-term repairs (IRI around the norm extreme) by e.g. milling surfaces, and places of an increased demand for restoration works (IRI in the B class).

There are spreadsheets, programming libraries and even ready-to-use calculation programs (e.g. ProVal) containing the implemented method of IRI calculation on the basis of input data of the road profile. In the case of this project, having the surface profile data obtained by the use of the Walking Profiler, there is no reason why the data should not be analyzed by the use of one of the above methods and IRI determined for individual sections of the tested area.

3. Walking-Profiler

A Walking-Profiler is a measuring device for measuring the longitudinal profile of the road surface. Its main element is a high-quality inclination recorder that defines the real angular position of the device relative to the vertical axis of the globe (that is, the inclination from the vertical gravity). The second element is the rotary encoder mounted on one of the wheels. Its task is to count revolutions of the wheel, and thus the measurement of the distance covered by the device. The encoder used in the device allows for the registration of up to 40,000 steps per revolution, significantly reducing measurement uncertainty. For example, the distance measurement on the test section of 1 kilometer deviated from the real distance by 12 centimeters, so a measurement error was 0.012%.

These elements allow to obtain information about the distance of any measuring point from the beginning of the test section and also the device inclination at this point. By taking the data at specified distance intervals, measuring the value of consecutive inclinations, making transformation of inclination (with respect to distance) to a height andsumming up the received heights, a function describing the exact shape of the covered testing section can be created.

In order to do this, the following assumptions must be met:

- The values of the measured heights have a relative nature; this means that the starting point of the tested section equals zero, the rest of the points are counted in relation to it;
- A measuring step should be as small as possible. The smaller the value of the step, the more measurement points – the data describing inclination (heights); it entails a more accurate profile function. The standard measuring step is 1 mm-long, but this value can be modified if needed;
- The values measured by the inclination sensor brought together give a quite shapeless, and acute function. The results in this form are not suitable for further analysis and require a correction;
- The construction of the device with a track of wheels equaling 500 mm introduces automatic averaging (filtration) of the collected data. It works like a low-pass filter.

Various factors have an influence on the deformations described in point 3. The construction of the device and installation of the sensor are burdened with a technological error. The measurement performed by the sensor is also burdened with a measuring error. The device itself works in dynamic conditions, that is, it does not stop at a specified distance and it does not stabilize in order to take a sample. Additionally, the measurement is taken only in the course of movement, which also disturbs the measurement. Therefore, the initially received inclination function must be subjected to rectification. There are a lot of methods and algorithms for analysing distorted signals. Probably the best and also the most commonly used one is the Kalman filter [5, 6]. The rectified inclination function may be finally regarded as an optimum and in such a form it can be used to determine the correct function of the profile.

4. Planograph

A Planograph is a measuring device used to measure the height of local vertical deformations of the pavement relative to the plane determined by the wheels of the device. The official design guidelines can be found in standard BN-68/8931-04 [3]. Since the time when the standards were introduced, technology has been constantly changing, and thus some construction changes are permitted, for example, in terms of the shape of the frame, structural materials, and the use of electronic systems (measurement with digital registration data). However, elements such as a diameter and a track of wheels must be maintained in accordance with the guidelines.

The mechanical design of the planograph contains 4 main parts:

- The Trolley Frame (1) on the skeleton of which the other items are mounted. The standard allows for freedom in this regard, provided that it does not affect the correctness of the other points. The weight of the device should be evenly distributed so that the center of gravity is exactly in the axis of the sensor. It is necessary to use construction weights when this condition is not met;
- Wheels (2), with a diameter of 200 mm. The device has 14 wheels, 7 on each side (front, rear). The specific wheels are paired with each other. The paired wheels are arranged symmetrically in equal distances relative to the axis of the sensor. The distance between other wheels and the axis of the sensor is deliberately uneven. It is aimed at catching the

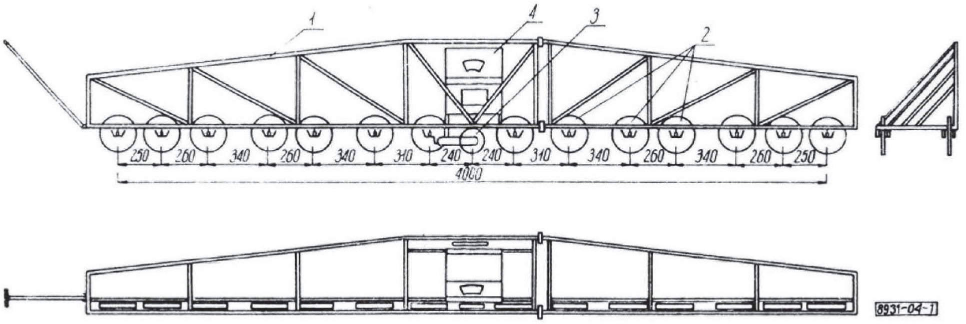

Fig. 1. Technical diagram of a Planograph

maximum range of the waves [6] of unevenness that may be found on the roadway. The device also has one additional wheel, placed on its side. Its only function is to maintain the device in a vertical position, so that it did not fall out. This wheel is not important in the procedure of measurement and has no influence on the results obtained;

- Measuring Wheel (3), with a diameter of 150 mm. It is mounted centrally in the axis of the device, on the resistanceless rail or a similar element that allows free 'top-down' movement of the wheel in relation to the device. The sensor wheel, when passing through a rut or a bump, rises or falls, which enables to register the profile of the pavement;
- The Measurement Table (4). It can be any mechanical design, an electric or electronic one, that enables to record the changes in the position of the measuring wheel for the entire duration of the test. In the first versions of the device there were recorders mounted on the tape, which drew graphs on graph paper (like a seismograph). Now electronic sensors and microprocessor systems are applied. They allow to make accurate measurements and record data on a digital medium.

Additionally, according to the norm the following requirements must be met. The measurement accuracy cannot be worse than 0,1 mm. Secondly, the test must be carried out in a continuous mode, i.e. it must register the sensor's values in the continuous movement of the device.

5. The Planograph Simulator

The Planograph Simulator is a software for numerical calculations that can be used to model the response of a planograph, mainly to determine the exact position of the sensor on the basis of the data of the profile of the road covered by the device. The road profile data can be obtained in any way. As mentioned in an earlier chapter, to generate data of the road profile, the Walking-Profiler was used.

5.1. The physical model of the planograph-analysis

The centroid and the axis of symmetry in relation to the vertical axis of the device. In this axis the measuring sensor is placed in the form of a circle of a certain diameter. It was assumed that the starting point of the sensor is located at the intersection of the axis of symmetry and the axis of the wheels. This point is a point of reference for all calculations. The distribution of wheels is symmetrical on each side. The measuring base is the so called ‘zero line’. This is a straight line designated by a tangent line to all wheels at the point where the wheels and the test surface meet. The sensor wheel moves always in a line perpendicular to the zero line. Due to the symmetry of shape and weight, the device will always be based on the tested profile at least by one of the ‘front’ wheels and at least one of the ‘rear’ wheels. The wheels on which, at a given moment, the device is the supported are called the supported wheels. This assumption is referred to as the assumption of minimum supporting. It has been used in all calculation methods.

5.2. Calculation of the planograph’s position on the profile

Method No. 1 entails the maximum simplification of the model without taking into account its real inclination. The support point of the wheel is treated as a material point, the highest point under the circumference of the wheel. The zero line is always horizontal to the profile. The left supported wheel is the one which stands on the highest profile point. The same goes for the right wheel.

A simultaneous assumption that the zero line is always horizontal and an assumption of a minimum support, causes an interesting effect. Because there is at least one support point on each side, theoretically there is a ‘break’ in the middle of the device.

The base point of the sensor (the zero point), from which the height is determined, should be therefore determined either by the average value of the difference in height (inaccurate), or by an average difference in height taking into consideration the weights-distances of the supported wheels from the middle.

The method is very fast and easy to implement, but causes a lot of errors when the difference in height between the supported wheels is significant (there are inclinations present which are not taken into account). What is more, this method does not provide for a situation that may occur in reality, when as a result of the inclination (which is not taken into account), the most external wheels on one side are below the presupposed height and thus possibly supporting at some point, which as a consequence may lead to raising one side of the device, interfering with the indication of the sensor.

Method No. 2 assumes the average simplification of the model, taking into account the real inclination. The support point of the wheel is treated as a material point, the highest point under the circumference of the wheel. The weights of the height for the supported points for wheels are counted as the quotient of the height (the vertical distance of the possible supporting point of wheels in relation to the level of a temporary zero line) and the width (horizontal distance of the supporting point of the wheel from the axis of the sensor).

The method is fairly simple to calculate with greater calculation complication from the previous method. It is accurate, but only if the wheels are supported exactly in the middle point of the wheel’s circumference. When in reality the wheels are supported slightly further than this point, there are errors. The greater the difference between the theoretical support point and the real one, the greater error may occur.

Method No. 3 assumes no application of any simplification. The method takes into account the real inclination angle. The supporting point for the wheel is treated as a real point profile, on which the wheel is supported. The zero line is determined by the real supported wheels.

The method assumes calculation of the real supporting point for each of the wheels. Assuming that the measurement step is taken every 1 mm, when a wheel diameter is 200 mm, this gives 200 checks for one wheel, giving 2,800 checks for all wheels at each step in the test profile. The method of calculation of weights is the same as in the previous method.

The method is complicated and of high calculation complexity, due to repeated calculation and checking supporting points at each measurement step. However, the method is the most accurate one.

Determination of the appropriate supported wheels (in methods 2 and 3) consists in picking the wheels of extreme weight results on each side. For example, if the device is located on a perfectly flat profile, the weights will equal zero, because all the supporting points of the wheels will be on the same height. Otherwise, the device will be leaned to one of the sides, thus all height values on this side must always have negative values. Depending on the direction of inclination, a pair of weights must be taken into account – 'the smallest left one, the largest right one' or 'the largest left one, the smallest right one'.

This is an iterative method. When determining the height of each of the wheels and the appropriated supported wheels, it is necessary to check if the remaining wheels meet the requirements (the wheels are mounted on a rigid frame, and they all must lie in one line). If some of the wheels 'fell under the profile', it would be necessary to 'raise them' to the profile height, to raise the other wheels proportionally and repeat the procedure of counting the inclination. If in the next iteration the numbers of the supported wheels repeat, it will mean that the appropriate supported wheels have been determined correctly. When having the supported wheels determined, it is possible to mark the inclination, the real location of the base point of the sensor, and then make a calculation for the sensor's measurement.

5.3. Calculation of the sensor's wheel's position

Having the knowledge of the 'zero' point of the sensor (the intersection of the axis of the wheels with the axis of the sensor), calculated with the use of the above methods, it is possible to calculate the sensor's wheel's position. In order to do this, in theory, it is necessary to lower the sensor perpendicularly to the calculated inclination line until the sensor stops on the road profile. In practice, this requires more precise calculations, so an iterative method is applied.

The first step is to lower the sensor in the Y-coordinate until an obstacle is encountered in the form of the profile and to specify its height. Then, it is necessary to compare the X-coordinate of the sensor to the X-coordinate of the point (for the same height as the sensor) of the line perpendicular to the line of inclination going through the 'zero' point of the sensor. If this value is higher than the allowable measurement error, the sensor needs to be moved in the X-coordinate so that the middle point of the sensor temporarily lies on the perpendicular line. Temporarily, because the calculation of the sensor height needs to be repeated (the profile points under the wheel sensor must be checked) for a new location, it may turn out that the sensor in the new location will change its height, and thus it will be required to once again move the sensor in the X-coordinate in the direction of the perpendicular line. The process should be repeated until the values fall within the limits of the permitted error.

It is also necessary to mention that the sensor, due to its construction, measures the height in a determined way. A sensor in the form of a circle of a certain diameter will not be able to measure a small rut, because its diameter will prevent it from ‘falling into’ them. With a small measuring step, the sensor will detect all, even the smallest bumps. Therefore, it is recommended to use small measuring steps in order to avoid a situation where during the tests big bumps are skipped, which, during the actual trip will be felt, and which will not be seen during the tests. Such a situation can be found for example in the literature [4] where it is described in detail.

6. Conclusions

The project described in the article consists of two parts. Walking-Profiler was built in accordance with previous assumptions. Thanks to this device, it is easy to obtain the actual longitudinal profile, the so called ‘true profiles’ [6], covered by the device. This data can be used later to establish the International Roughness Index for the test section with the use of one of the methods described in Section 2. IRI.

The second stage of the project was the creation of numerical software, which would model the behavior of the actual device – a planograph moving along this profile, and the behaviour of its measuring sensor. In the previous section the analysis of this problem was presented and several possible algorithms for dealing with specific situations were shown. It was stated that the most appropriate method to calculate the device’s position will be method No. 3. Although in comparison to other described methods method 3 is most complex in terms of the numerical method, it has the largest calculation complexity and is the most difficult one to implement, it provides the most accurate results and generates the fewest errors. Then, the method was used for determining the supported wheels on the basis of the value of the extreme weights on each side. Having the exact location and inclination of the device, the values calculated by the measuring sensor can be obtained.

By repeating this procedure for all points of the test section, a very accurate print of the values can be obtained as they were indicated by the sensor of the actual planograph if it covered a given profile. The method proposed in the article, however, allows to get exactly the same results as if the planograph was used in the tests, but without the use of a physical device and testing only using a simulator. The proposed method is less troublesome and, above all, disproportionately more accurate, because the measurement takes place in somewhat quasi-static conditions, the applied electronic components have a significantly better measuring capacity, there is a lack of moving components and the problems with technical support issues of the planography operation are completely eliminated.

References

[1] Rozporządzenie MTiGM w sprawie warunków technicznych dla dróg publicznych i ich usytuowania, Dz. U. Nr 43, poz. 430, 2 marca 1999.

[2] Rozporządzenie MTiGM w sprawie przepisów techniczno-budowlanych dotyczących autostrad, Dz. U. Nr 12, poz. 116 , 16 stycznia 2002.

[3] BN-68/8931-04, *Pomiar równości nawierzchni planografem i łatą.*

[4] Chabowski E., Osysko A., *Badanie równości podłużnej planografem – przypadkowość czy dokładność*, Opracowanie Techniczne, 06-2012.

[5] “Filtr Kalmana”, [in:] Wikipedia, Free Encyclopedia.

[6] Sayers M.W., Karamihas S.M., *The Little Book of Profiling*, University of Michigan, September 1998.