On laser scanning, pavement surface roughness and international roughness index in highway construction

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ABSTRACT

The paper reports data from the research project where the objective was to develop and validate a tool that would be publicly available and would leverage the point cloud data commonly acquired on sites to calculate the pavement surface properties such as the International Roughness Index and Roughness. To do so, a unique RIRI program was written in Python to streamline the point cloud data analysis. The program is publicly available under the GNU General Public License. Further, the paper presents data from three test sections where the developed methodology was used to calculate the pavement smoothness properties from a point cloud and compared to classical, reference, methodologies, such as the rod and level and precise levelling. The paper focuses on the variability and precision of all methodologies. It was found that the Pearson type IV distribution is a fitting descriptor for histograms calculated with the help of Freedman and Diaconis's law from rectified slopes and roughness values with regard to its fitness and use of its parameters for the pavement surface smoothness description.

Keywords: Asphalt, Durability, Safety, Software, Testing

1. INTRODUCTION

The choice of a proper pavement construction technology has always been a task combining engineer's knowledge and experience. The goal is to effectively construct a desired pavement layer while meeting all standardized requirements, design criteria and contracting agencies' demands. However, many disorders whose occurrence is linked to an improper mix design, errors in the mix production, its water content, and mistakes in the laydown process, such as the temperature loss, paver stops, improper compaction, result in an immediate decrease of the constructed layer quality. One of the criteria for a flexible pavement is its surface smoothness. It has a significant effect on the surface water runoff and the ride quality, and, most importantly, traffic safety [1]. Some of these disorders are present right after the layer construction, and some of them take their effect when traffic loading and weather conditions occur during the pavement's lifetime. Janoff suggested, in his extensive work [2] based on the data collected over ten years from more than 400 test sections, that the initial smoothness is related to the pavement long-term roughness and durability in regard of the pavement cracking and overall deterioration. These findings are today proved by the mechanical analysis addressing the effect of flexible pavement viscoelasticity in relation to dynamic loading increased with the pavement surface roughness [3]–[7].

It was proved by [8] that highway users judge the condition of a highway by the riding experience when they travel over the highway. The pavement surface smoothness is an important parameter for road users not only from the perspective of their riding experience, but it is also one of the determinants of road user cost, as indicated in [8].The need to measure the pavement surface smoothness led to the development of devices ranging from very simple and still in use devices like the rod and level, profilographs, where the Californian profilograph may be mentioned as one of the early developed and still in use devices. Further, with the advances in technology, the need led to many developed automated devices to measure the pavement smoothness [9], [10].

The wearing course roughness has been used in many project specifications over the US and European countries to set pay adjustments based on the desired threshold. Nowadays, even in Public-Private-Partnership schemes and advanced design-build projects, roughness is one of the specifically set quality criteria. Furthermore, advanced design techniques and the use of construction machine control systems help to achieve these contract requirements [11].

Although the definition of smoothness indicators varies over states and countries from the International Roughness Index (IRI), the Profilograph Index (PrI), the Mean Roughness Index (MRI), the Quarter-car Index, the root-mean-square vertical acceleration and the rod and level surface smoothness measurement (roughness), whose review may be found in [12]–[16], the value of smoothness should be well recognized as a useful indicator of the pavement serviceability performance and the quality of pavement layers should be periodically checked.

2. METHODOLOGY

The ability to use 3D laser scan data acquisition systems for the pavement profile properties determination was already proven by others [17]. However, the use of laser-based devices in civil construction is increasing. The laser technology is used for construction machines' navigations, surveying, the construction progress monitoring and quantity checks. The goal of the research project was to develop and validate an applicable methodology which would allow leveraging the already recorded point cloud data and provide feedback to contractors, laboratories and contracting agencies on the constructed layer smoothness, without a need for extra single purpose measurements. The other goal was also to validate a free to use and modify tool that may be used at the construction site and by participating laboratories.

2.1. **Test sections**

Three test sections were selected to demonstrate the applicability of the RIRI program and acquired point cloud data to measure the pavement surface smoothness. The test sections were selected so that the range from smooth roads to rough pavement surfaces would be covered within the research project scope.

The first test section is a two-lane urban road. The selected section is 510.00m of a straight urban road, with no intersections or driveways. This test section was expected to have the smoothest pavement surface properties. The laser scan measurements together with the rod and level and precise levelling were done two days after the pavement wearing course laydown.

The second test section is an arterial road, with a high traffic capacity, a four-lane expressway with one lane dedicated for parking in each direction. The total length of the test section is 1.618.00m. The surface course was laid down using the total station machine control system. The wearing course can be classified as an open graded surface. The test section is in a highly urbanized area so the semi-open graded wearing course was placed for the purpose of noise pollution reduction. Both

measurements, the laser scan and the classical rod and level and precise levelling, were done two months after the new wearing course placement.
The third section is a cement stabilized base course of wye (railway triangular junction). The layer surface properties were measured two days after its placement. This test section is expected to have the roughest properties regarding the environment conditions, stabilized layer maximal nominal aggregate size and the fact that it is not a pavement wearing course. The length of this test section is 160.00m. The methodology scheme can be seen from figure 1.
The surfaces were cleaned from loose particles with road sweepers before the surface properties data were acquired on the site.

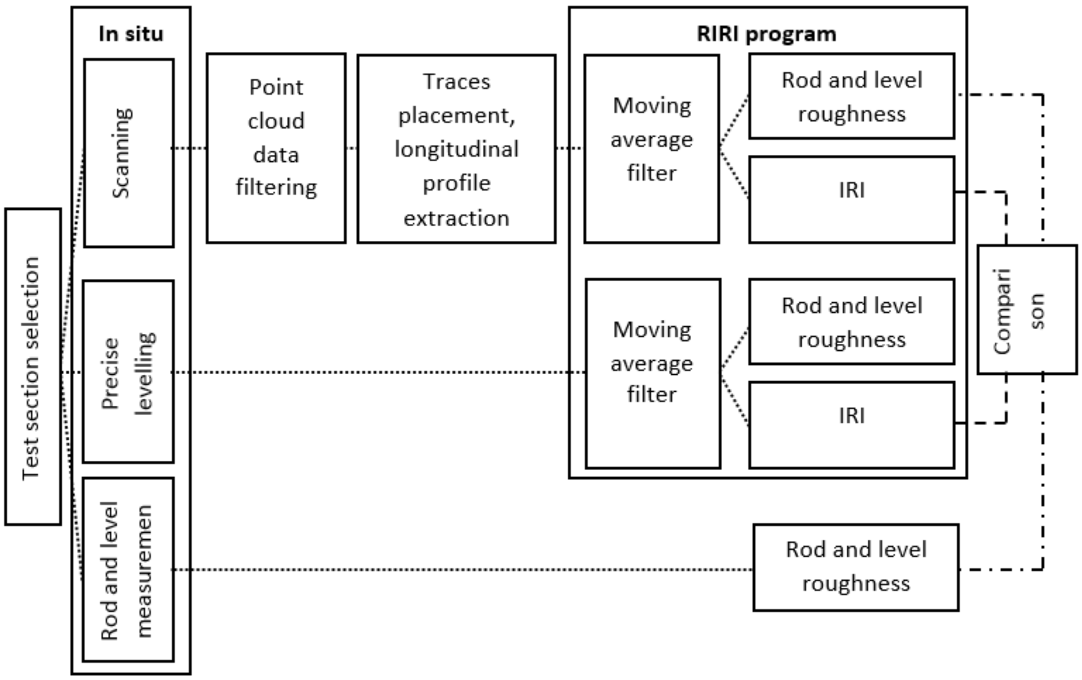

Figure 1: Research project methodology scheme

2.2. International Roughness Index

Two pavement profile characteristics to address the pavement surface smoothness were selected. IRI was recognized by the World Bank as a superior criterion for the pavement smoothness measurement [8] and for its spread use over states, European countries and its inclusion in the Czech national standard [18], and the proposed European standard [19] was selected as the main further considered surface smoothness index.
IRI was computed from a longitudinal road profile measurement using a virtual response type system, the quarter-car simulation, running at a speed of 80 km/h. The quarter-car simulation was applied on the longitudinal profile derived from the filtered longitudinal profile. The longitudinal profile was created from the 3D surface by positioning the alignment in the desired trace of the profile. The profile was filtered with a moving average so that the filtered profile used for further analysis would contain points with a 0.25m spacing. The so called RIRI tool was used to calculate rectified slopes for each longitudinal profile point by applying the quarter-car simulation. IRI was calculated from point cloud data based on:

- Each IRI is computed from a single longitudinal road profile.
- From each test section, five longitudinal profiles were created by placing five parallel alignments.
- The spacing between the alignments was 0.25m and they were always created within pavement lines.
- The filtered point cloud data had a point density higher than 100 points/m^2, so that the maximal sampling interval criterion of 125 mm, in [19], was met.
- The 3D laser scan resolution is 0.2mm.
- The created longitudinal profile was smoothed with a moving average whose base length is 250 mm.
- The smoother longitudinal profile is assumed to have a constant slope between the sampled elevation points.
- IRI is calculated from the smoothed longitudinal profile using a quarter-car simulation, with specific parameter values, at a simulated speed of 80 km/h.

- The simulated suspension motion is plotted in the form of a rectified slope linearly accumulated and further divided by the length of the profile to calculate IRI.

To validate the acquired data precision and their usability for the pavement index calculation, the longitudinal elevation profile was measured with precise levelling in the right wheel path of the outer pavement lane. The points from precise levelling were already taken with a 0.25m spacing so that the smoothing step could be omitted during the data processing. This longitudinal profile was used as an input file to the RIRI program to calculate the accumulated rectified slope and IRI.

2.3. **Roughness**

Roughness under the rod and level was measured at each test section. The rod and level measurements were done in one trace located in the outer lane right wheel path for all test sections. The measurements were taken only in one trace for each section due to the labour cost and the limited time window.

The roughness under the rod and level was calculated from point cloud data for the same five traces as used for the IRI calculation in each test section. The placement of these five traces, in the outer lane right wheel path for all test sections, was determined from the laser scan data only.

3. RIRI PROGRAM

To streamline the point cloud data analysis, the so called RIRI program was written in the Python language [20]. In order to allow for the program's public use, the RIRI graphical user interface was developed as part of the research project. The program is capable to filter the input data with a moving average so that the filtered longitudinal profile with points with a 0.25m spacing is obtained for further analysis. The principle of the quarter-car simulation is further applied on the filtered longitudinal profile and the rectified slope is calculated for each point. These data can be plotted in a chart, see figure 2. The plotted figures allow zooming and the location of areas where the computed values are of interest. Any profile data may also be imported into the RIRI program as an ASCII file, to perform IRI and the rod and level analysis. The roughness output or IRI output files are generated together with created plots, so that the data may further be used to locate the desired areas where the Roughness and IRI values vary from the desired threshold in any other program.

One of the broadly known tools for the pavement profile analysis is the ProVALsoftware [21]. However, the ProVAL licence does not allow modifying the source code, thus it would not allow us to achieve the desired goals. The RIRI program was developed with the aim of being of the greatest possible use to the public, and the best way to achieve this was to make it free software which everyone could use, redistribute and modify. Unlike ProVAL, the RIRI program is licenced under the General Public Licence [22]. The program is available at permalink: *The link has been removed with respect to undertake double-blind review.*

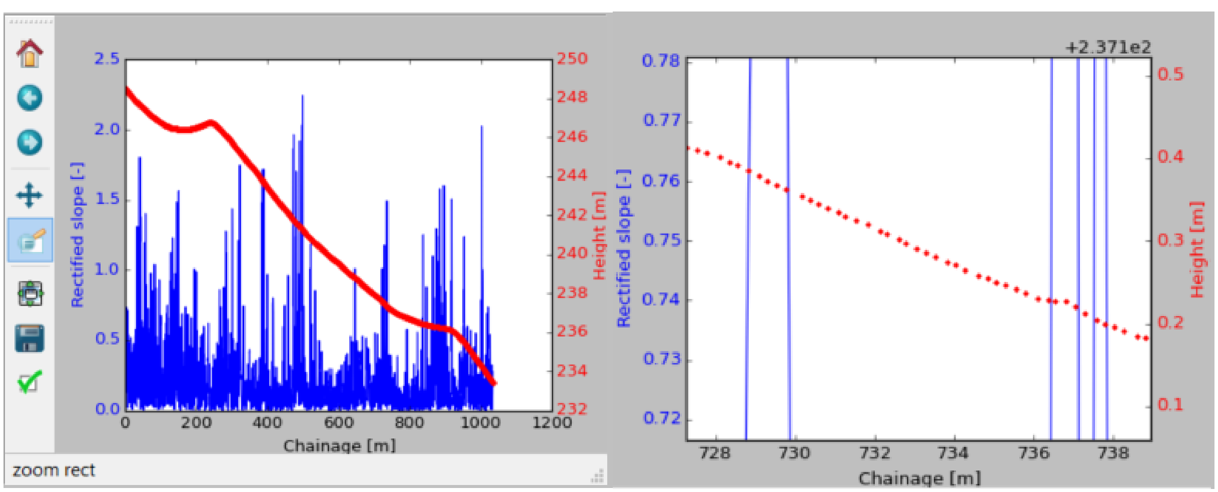

Figure 2: IRI plot in the RIRI program and data zoom

4. TEST DATA INTERPRETATION AND APPLICATION

4.1. IRI

Figure 3 shows the comparison between the rectified slopes calculated from the laser scan and the rectified slopes calculated from the precise levelling of the first test section. It is troublesome to judge on the proposed method's validity only from the rectified slope plot and IRI as the rectified slope average. In figure 4, a typical Box-and-Whisker plot for the calculated rectified slope, and also for the first test section may be seen. Box-and-Whisker plot characteristics are further listed in table 1. The laser scan data acquisition provides a lower rectified slope variability as is also seen from the smaller interquartile range of all rectified slopes calculated for the profiles from point cloud data.

As may be seen all rectified slope values have a high variability and contain outliers. These outliers refer to construction disorders mentioned in the introductory paragraph, thus they have an importance for the quality of the pavement structure hence they will be further studied together with IRI. The position of the outliers and its detail may be located using the RIRI program as shown in figure 2.

Another descriptor, a histogram, may be used to distinguish the surface smoothness characteristics in terms of calculated rectified slopes. In this way, the density distribution functions may be used to compare the calculated rectified slopes if the traces used for data acquisition are not identical. Because each filtered longitudinal profile contains more than 400 values and the outliers are also of our interest, Freedman and Diaconis's law is chosen to set the non-oversmoothed histogram class width rather than the commonly used Sturges´ law [23]–[25]:

$$h = 2(IQ)n^{-1/3} \tag{1}$$

where h is a class width, IQ is the sample interquartile range.

The Pearson type IV distribution function was used to estimate the shape of the rectified slope density distribution [26]:

$$P(x) = \frac{a}{\left[1 + \frac{4*(x-b)^2\left(2^{\frac{1}{d}}-1\right)}{c^2}\right]^d} \tag{2}$$

where x is an independent variable, the rectified slope class, a is the amplitude, b is the centre of the Pearson type IV distribution, c is the full width at half maximum and d is the Pearson type IV distribution parameter.

The following abbreviations are used in figures and tables: i-th test section trace (Ti), rectified slope (RS), laser scanning (LS), precise levelling (PS), average values from five traces (AT) and Pearson product-moment correlation coefficient (PCC). Data approximation may be seen in figures 5 and 6. The so called average trace may be used as a suitable representative trace, when all Box-and-Whisker plot parameters for the rectified slopes obtained from point cloud data are compared, see figure 4. The same trend, where the rectified slopes calculated from point cloud data exhibit a lower variability than the rectified slopes calculated from point cloud data, is evident from the data from all test sections. The Pearson type IV distribution parameters are listed in table 1.

It is proved that the rectified slopes and IRI (r = 0.94) obtained from point cloud data correlate well with those measured with a classical methodology.

The Pearson type IV distribution is capable to approximate the rectified slope's histograms well as may be seen from the coefficient of determination ranging from 0.89 to 0.65. The parameters like the amplitude, the centre position and the full width at half maximum of the Pearson type IV distribution also have very good correlations when both methodologies are compared. This implies that the Pearson type IV distribution is a fitting descriptor for the calculated rectified slopes histogram and that both methodologies used to obtain these data have a good correlation.

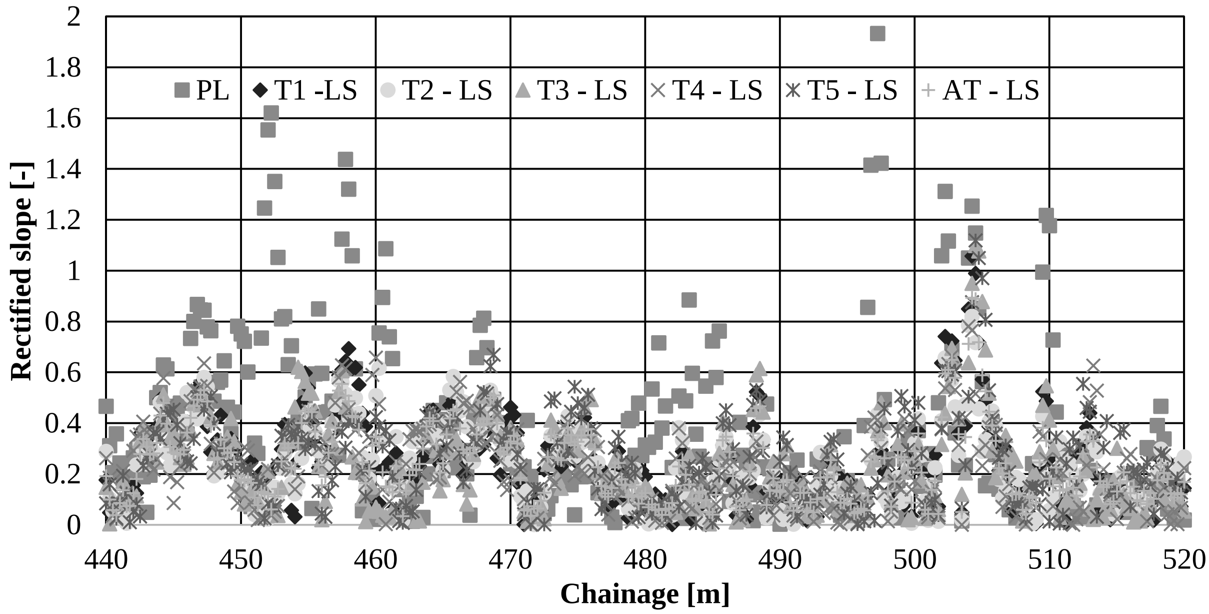

Figure 3: Rectified slope over a selected test section length, test section # 1

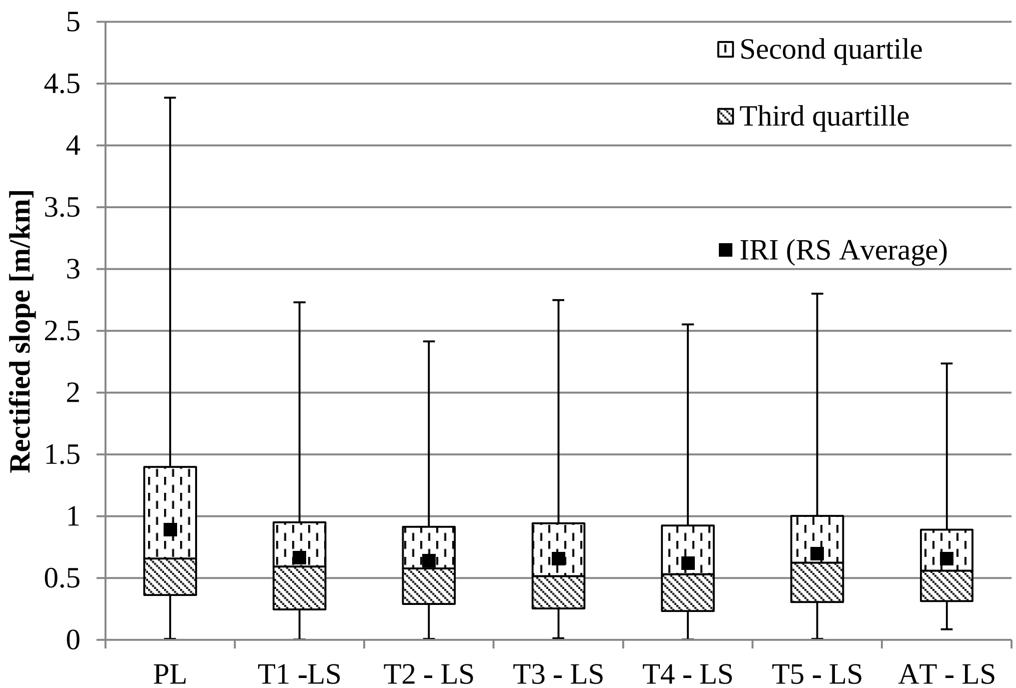

Figure 4: Box-and-Whisker plot, Rectified slope and IRI, test section # 1

Table 1: Comparison of Rectified Slope and IRI and Parameters of Pearson Type IV Distribution

	Test section #1		Test section #2		Test section #3		PCC between PL and AT - LS
	PL	AT - LS	PL	AT - LS	PL	AT - LS	
IRI (RS Average)	0.894	0.657	4.662	2.004	6.346	4.190	0.94
Standard Deviation	0.715	0.437	4.377	1.447	5.099	2.730	0.91
Min	0.008	0.086	0.006	0.074	0.074	0.076	-0.39
Q1	0.362	0.312	1.618	0.951	2.403	2.214	0.95
Median	0.657	0.560	3.480	1.688	5.086	3.578	0.95
Q3	1.398	0.890	6.051	2.529	9.320	5.502	0.96
Max	4.386	2.236	28.008	9.593	26.792	15.599	0.87
Bottom	0.362	0.312	1.618	0.951	2.403	2.214	0.95
Third quartile	0.295	0.248	1.862	0.737	2.683	1.363	0.97
Second quartile	0.741	0.330	2.571	0.842	4.234	1.924	0.97
Pearson type IV distribution parameters							
a	46.127	11.841	11.381	0.539	17.268	0.627	0.99
b	0.475	0.261	4.110	3.856	1.802	4.212	0.72
c	0.170	0.011	1.380	0.871	6.105	1.976	0.97
d	0.330	0.879	0.030	0.077	0.600	0.002	-0.05
r2 CoefDet	0.871	0.679	0.815	0.603	0.848	0.888	-

4.2. **Roughness**

The measured roughness is usually expressed in the form of a histogram where the x axis is the roughness depth in millimeters and the y axis is the number of occurrences. The pavement quality specifications then allow the roughness depth under a certain threshold. If the same data analysis principle as the one used for the IRI comparison is used, by fitting these histograms in equation 2 we obtain the parameters of the Pearson type IV distribution. The parameters and correlations between both methodologies are presented in table 2.

It is believed that the third test section exhibits such high roughness due to the layer maximum nominal aggregate size of 32mm. Even if this layer is well compacted, the porosity of the surface is partly captured when point cloud data are acquired with the laser scan.

From the values of the coefficient of determination, it may be concluded that the Pearson type IV distribution fits well with the measured roughness. Further, when we look at the PCC values, it may be concluded that both techniques, the laser scanning and the rod and level, are capable to determine comparable results of the surface roughness.

The correlation between the *a* parameter of the Pearson type IV distribution suggests that both methodologies are capable to determine a comparable amplitude. However, *b* is negative in two test sections, thus the high correlation of the *b* parameter does not imply the correlations of mean values as they have to be positive from the principle of measurement.

Table 2: Comparison of roughness described with Pearson type IV distribution

	Test section #1		Test section #2		Test section #3		PCC between PL and AT - LS
	PL	AT - LS	PL	AT - LS	PL	AT - LS	
Pearson type IV distribution parameters							
a	1598.81	249.53	36.42	43.67	11.46	128.10	0.91
b	-0.522	1.451	2.584	1.830	-22.851	-0.037	1.00
c	0.050	0.711	0.700	0.035	2.050	0.004	-0.78
d	0.522	0.999	0.868	0.227	0.024	0.172	0.16
r2 CoefDet	0.857	0.990	0.903	0.769	0.769	0.868	-

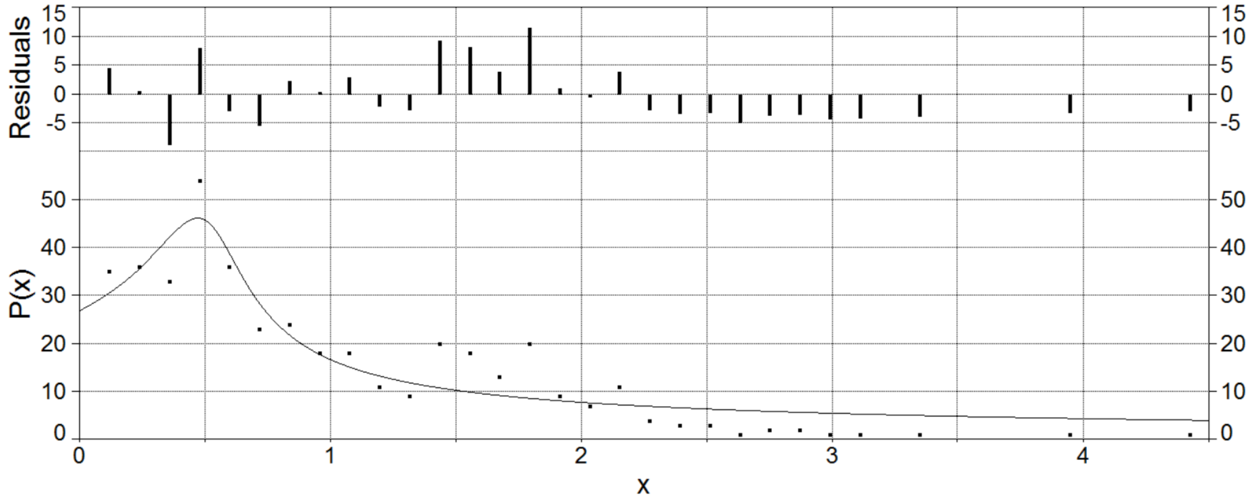

Figure 5: Rectified slope histogram approximated with Pearson type IV distribution, PL, test section # 1

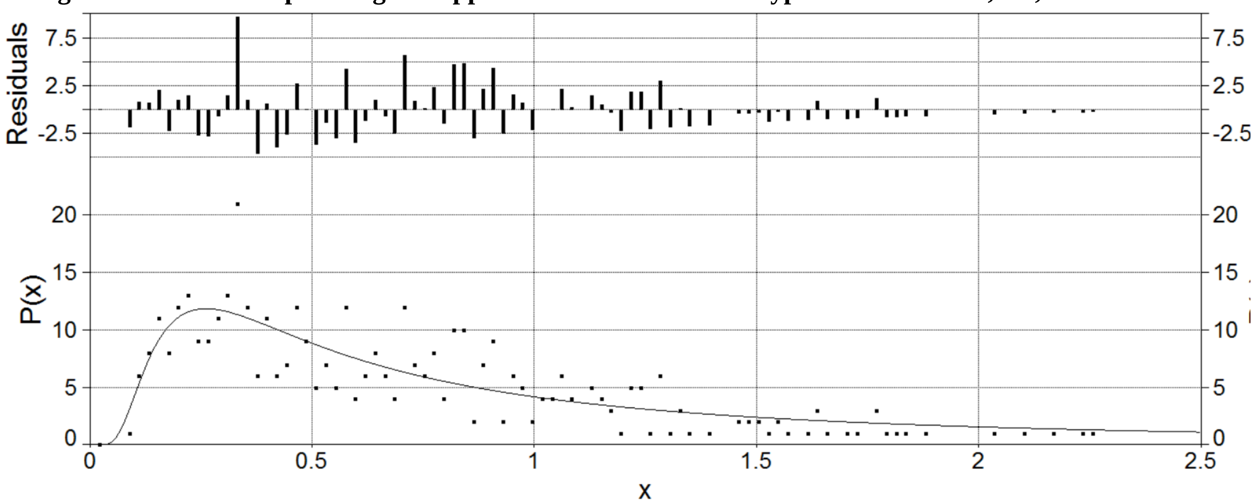

Figure 6: Rectified slope histogram approximated with Pearson type IV distribution, AT – LS, test section # 1

5. CONCLUSION

The objective of the research project was to develop a free to use and modify program capable to calculate IRI and roughness properties of pavement layers from point cloud data and statistically evaluate whether the point cloud data commonly acquired on sites are so high-quality that they can be used for the surface smoothness parameters calculation. The comparison was done with the methods broadly used to measure pavement roughness – rod and level and IRI – precise levelling. The following are the key conclusions and findings from this study:

The most important conclusion from this project, in the authors' opinion, is that the point cloud data commonly acquired on the site may be used to calculate the surface smoothness properties such as IRI and roughness. The standard deviation of IRI calculated from a point cloud was found to be lower than the standard deviation of IRI calculated from the longitudinal profile measured with precise levelling.

This was done with comparison to classical methodologies for measuring roughness – the rod and level measuring and precise levelling to measure the pavement profile and calculate IRI.

It was found that the average rectified slope from five parallel traces on a point cloud is the suitable criterion when both methodologies are compared. The average trace provides sufficient accuracy when the average rectified slope (IRI) needs to be used and when the rectified slope variability is of interest.

It has been found that the RIRI program is a useful tool for streamlining point cloud data analysis and it may be used for the pavement surface IRI and roughness calculations. The program contains a data viewer that helps to locate sections with a reduced surface quality in regard of smoothness and take appropriate further actions.

The histogram descriptor was used to analyze the rectified slope and roughness. Class widths were determined using Freedman and Diaconis’s law. The Pearson type IV distribution was found to provide a reasonable approximation of both rectified slope and roughness histograms. The distribution parameters may be used for the data comparison.

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