Functional assessment of longitudinal road evenness by the weighted longitudinal profile (WLP)

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Abstract. Longitudinal evenness is one of the most important quality criteria of roads. Vehicles can be regarded as dynamic systems consisting of masses, springs, hydraulic dampers, anti-roll bar etc. They are governed by mechanical laws, i.e. when passing the road, the systems respond to the unevenness with vertical excitation. The impacts are multifaceted. In addition to effects on road safety, driving comfort and pavement loading, the dynamic forces enhance the vehicle's resistance to movement and consequently the vehicle's energy demand. This in turn leads to a higher energy consumption and subsequently to an increase in CO_2 emissions in road traffic. Against this background, the quality criteria for longitudinal evenness need to be defined by the mechanical impact on drivers and road construction in order to meet the concerns of road users and public authorities. For the assessment of longitudinal evenness, several indicators are in practice. In many countries, the IRI (International Roughness Index) is used for assessment purposes as well as for acceptance of construction works. However, the IRI depends on the velocity and, strictly speaking, on the mechanical system it represents. In order to overcome these shortcomings, the WLP (Weighted Longitudinal Profile) has been developed. Irregular, periodic and transient manifestations of unevenness can be individually addressed, safely detected and precisely located. It takes into account the entire range of speeds and dynamic properties relevant to road traffic. The paper covers the explanation of the indicator, the relationship to vertical dynamics, the deduction of limiting values and the application to road evenness data. The results are visualized and compared to the conventional approach.

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1 Introduction

1.1 Relevance of longitudinal road evenness

Evenness is an important characteristic of road surfaces. On one hand, the relevance refers to user interest, for example driving comfort and safety. On the other hand, evenness is an essential criterion regarding the evaluation of the road condition. Therefore, it is important to guarantee road evenness, both longitudinally and transversely. However, this paper focuses on the detection and evaluation of longitudinal road evenness.

In this context, internationally the International Roughness Index (IRI) is an important parameter [1]. This index is based on a quarter-car simulation, which includes dynamic oscillation characteristics of the vehicle, and depends on the velocity [2]. For this reason, the IRI is not used in Germany.

1.2 Current evaluation methods for longitudinal road evenness in Germany

In Germany, different measurement and evaluation procedures of longitudinal road evenness are considered for construction contract purposes and the evaluation of the road condition. The former aspect relates to the national standards ZTV Asphalt-StB [3] for asphalt pavements and ZTV Beton-StB [4] for concrete pavements. These standards refer to the first part of another national standard, TP Eben [5], which regulates contact measurements and associated evaluation procedures of road evenness. According to this regulation, the longitudinal evenness is mainly measured by using a four-meter rolling straight edge (see Fig. 1). This measurement method detects relative height deviations across the measuring path [5].

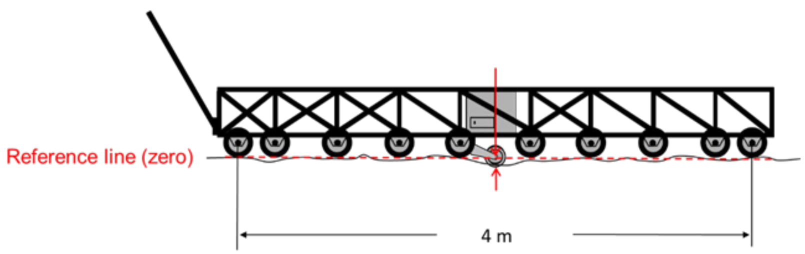

Fig. 1. Rolling straight edge.

The second aspect relates to the national standard ZTV ZEB-StB [6], which refers to the second part of the TP Eben [7] and regulates the measurement and evaluation of the road condition. In this case, the longitudinal road evenness is detected by high-speed measuring systems [7]. The evaluation is decisively carried out with the calculation of the parameter general unevenness (AUN) given in cm^3 (see Fig. 2), an indicator based on the power spectral density (PSD) of the longitudinal road profile in the right wheel path [6, 7].

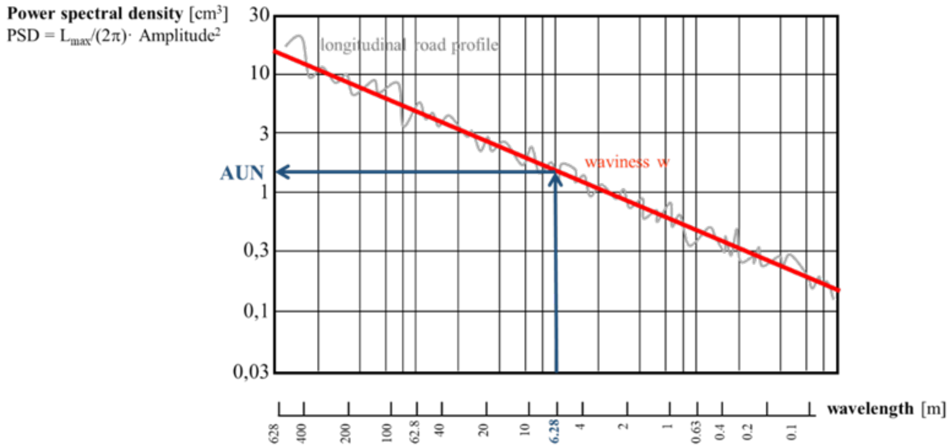

Fig. 2. Determination of the AUN.

1.3 Limitations of current evaluation methods for longitudinal road evenness in Germany

The mentioned evaluation methods have some limitations, which necessitate a revision of the evenness evaluation in Germany.

The main disadvantage of the rolling straight edge results from its limited length. Wavelengths longer than the length of the device, in this case four meters, cannot properly be evaluated. However, wavelengths relevant to the dynamic response of vehicles, and so to the longitudinal evenness, extend over a considerably larger range up to 50 meters [2]. Consequently, a major part of the wavelengths relevant to driving dynamics as well as periodic unevenness is not covered by this measurement and evaluation method. Besides the limited measuring range, due to the slow measuring procedure, the measuring method is consuming time and personnel resources and requires an intervention in the road traffic.

The AUN in turn is based on profile data that are gathered with non-contact, high-speed road profilometers. It is not limited in the measuring range, but covers wavelengths from 0.2 to 102.4 meters. However, the AUN represents only the average height of the Power Spectral Density and corresponds to the variance of the longitudinal profile. This indicator does not cover the amplitude-wavelength information or characteristic of the PSD. Therefore, the AUN is typically used to characterize the average unevenness of the longitudinal road profile. Periodic components or single obstacles in the pavement profile cannot be detected or described by this evaluation procedure. [6, 7]

2 Weighted longitudinal profile (WLP)

To overcome the mentioned limitations, the Weighted Longitudinal Profile (WLP) was developed. In Germany, this evaluation method is not mandatory in the case of constructions and road condition evaluation yet. However, the current draft of the TP Eben [8] stipulates a shift from contacting to non-contacting measuring methods for contract purposes in road infrastructure admission. The aim is to use high-speed road profilometers in the future. For a transitional period, the rolling straight edge simulation, based on the non-contacting measured longitudinal profile, will be the decisive method of evaluation. In the medium term, the Weighted Longitudinal Profile (WLP), as regulated in the European Standard EN 13036-5:2019 [2], is intended to be decisive for construction contract purposes. Therefore, the calculation steps of the WLP are presented in this paper, followed by some practical examples, which underline the advantages of this procedure.

2.1 Calculation steps of the WLP

The WLP is able to describe the whole range of unevenness characteristics – irregular, periodic and transient unevenness. Like dynamic response indicators, for example the IRI, it considers the influence of the wavelength on the dynamic effect of unevenness but, unlike the IRI, it is free of oscillating, decaying effects, which makes the WLP a non-directional evaluation method.

The calculation of the Weighted Longitudinal Profile (WLP) is based on a longitudinal road profile. The road profile is gathered by high-speed measuring systems and resampled with an increment of 0.1 meters. At least 2048 data points, therefore 204.8 meters of longitudinal road profile, are required to calculate the WLP. [7]

As illustrated in Fig. 3, the 204.8 meters of longitudinal road profile can be divided into the actual evaluation section, which is typically 20 meters located in the center of the calculation window, and a pre- and post-carriage, required for the first steps of the evaluation. The calculation of the WLP starts with generating the pre- and post- carriage for the first and the last evaluation position of the WLP. This is accomplished by a point reflection of the first 1025 profile points around the first and the last 1025 profile points around the last point of the longitudinal profile. As a next step, the WLP is calculated for this starting position (see Fig. 3 to the bottom left). The algorithm generates the WLP based on an evaluation length of 20 meters and consisting of 200 WLP points. The calculation section is moved by 20 meters and the procedure is repeated until the WLP of the entire longitudinal road profile is computed. The WLP record consists of increments of 0.1 meters. [8]

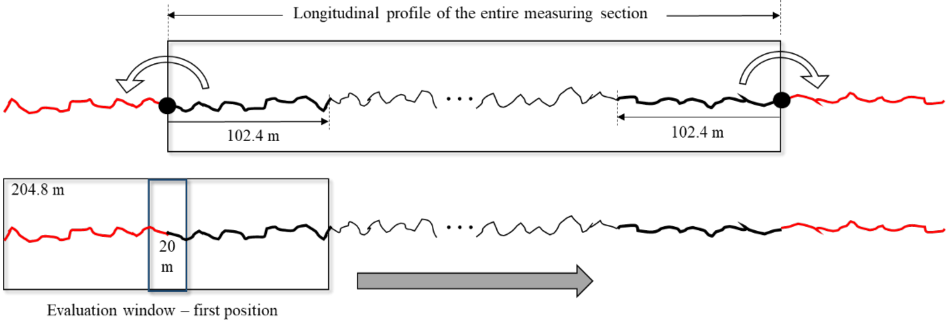

Fig. 3. Displacement of the WLP calculation.

For further evaluation, two indicators, standard deviation SBL and range DBL, are calculated. The calculation is also based on a 20 meters evaluation section. However, in this case, the calculation window is displaced on a sliding basis along the profile and the two indicators are assigned to the center position of the respective window. After having found the two numbers for the starting position, the calculation window is moved by an increment of 0.1 meters along the profile and the described procedure is repeated. The repetitions are continued until the last position of the moving calculation window is reached. As a result of the calculation, two additional records with a step size of 0.1 meters are generated, one for SBL and one for DBL [8].

The described WLP-calculation for each evaluation position consists of four calculation steps [8], which are outlined in more detail below.

As a first calculation step (see Fig. 4), the longitudinal road profile, consisting of 2048 profile points, is transformed from the space domain to the spectral domain by using the Fast

Fourier Transformation (FFT). Wavelengths between 0.2 and 204.8 meters are displayed. The spectrum is multiplied with a weighting function. The weighting function takes into account the typical amplitude-wavelength characteristics of road spectra and is equivalent to a slope (waviness) of 2.6 in the log-log PSD spectrum. Applying this weighting function, due to the differing driving dynamic importance, short wavelengths are given a higher weighting than long wavelengths. [2, 8, 9]

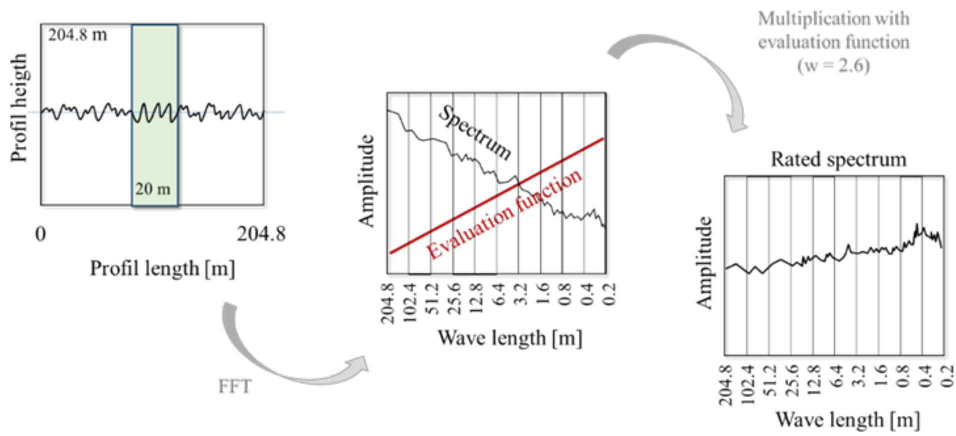

Fig. 4. First step of the WLP calculation.

As a next step (see Fig. 5), the weighted spectrum is divided into ten octaves. Each octave band is retransformed from the spectral domain to the space domain by applying an inverse Fast Fourier Transformation (iFFT). The results are ten weighted and filtered longitudinal road profiles consisting of 2048 data points each (P1 to P10). Merely 200 profile points in the center of these ten profiles (evaluation length of 20 meters) are kept for further computation. [7]

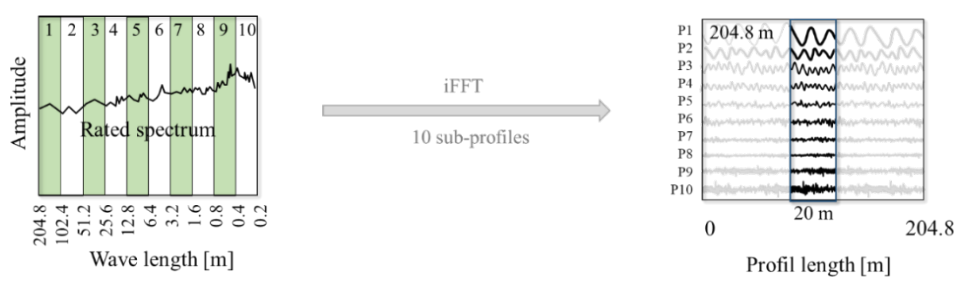

Fig. 5. Second step of the WLP calculation.

As a third step (see Fig. 6), by applying equation 1, the ten octave band filtered profiles are assembled according to their respective power contributions (σ_i) to the total power (σ_{tot}) giving the Weighted Longitudinal Profile (WLP). σ_i is the standard deviation of each profile P_i and σ_{tot} the standard deviation of the sum of profiles $\sigma(\Sigma P_i)$ [7].

$$WLP = \sum \frac{\sigma_i P_i}{\sigma_{tot}} \tag{1}$$

Fig. 6. Third step of the WLP calculation.

The last calculation step (see Fig. 7) refers to the calculation of the two indicators. A triangular window, consisting of 200 data points, having a minimum of zero in its vertices and a maximum of one in its center, is moved in increments of 0.1 meters over the WLP. For each position of the window, the respective 200 data points of the WLP are multiplied by the rating of the triangular window. The standard deviation (σ) and the range (Δ) are calculated and assigned to the center position of the window. Two indicators of the WLP calculation result from these numbers: the standard deviation SBL = 1.7320 * σ and the range DBL = Δ. The factor of 1.7320 accounts for the energy loss due to the triangular window. [8]

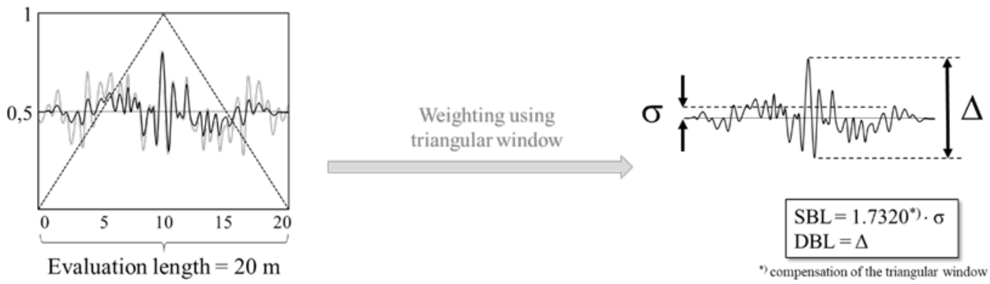

Fig. 7. Fourth step of the WLP calculation.

Fig. 8 shows an example of the resulting WLP, SBL and DBL records. For using equal limits for the evaluation, the DBL-value is divided by the factor 4 [8].

The calculated WLP strongly deviates from the measured longitudinal road profile. This is a result of the wavelength related weighting. The calculated two indicators, SBL and DBL/4, represent different unevenness shapes: A decisive SBL value represents a wavy shape of the road unevenness. By contrast, a decisive DBL value represents impulsive unevenness. If the ratio of the indicators is DBL ≈ 4 SBL, there is an irregular unevenness of the road surface. [10]

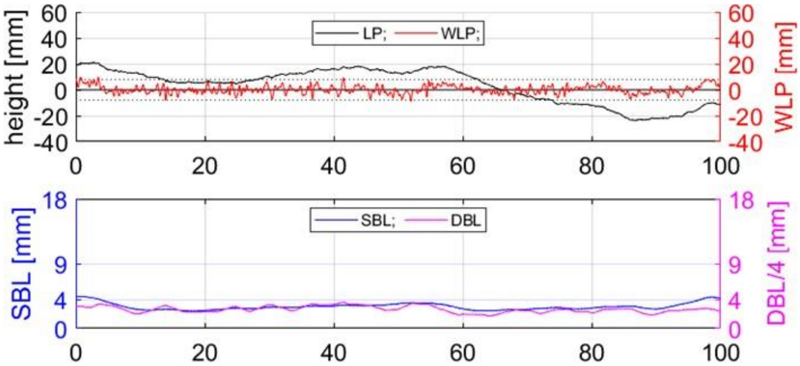

Fig. 8. Longitudinal road profile and resulting records of the WLP calculation.

For further evaluation of the WLP calculation, in particular with regard to construction contract purposes and the related implementation in the technical regulations, the RWTH Aachen University continued to develop the methodology on behalf of the German Federal Highway Research Institute (BASt). In this context, during the test phases of the WLP-method in the last three years, the relevance of periodic unevenness for the evaluation of the WLP has been pointed out. Therefore, two supplementary indicators are determined by calculating the autocorrelation function of the WLP: the level (see Fig. 9) and the length of the periodic unevenness. These indicators represent the harmonics-to-noise ratio and the duration of the periodicity, accordingly the driving dynamic relevance. If there were an irregular road unevenness, i.e. no periodicity, the level would approach zero. However, if there were a pure sinus periodicity, the level of periodic road unevenness would be one. [11]

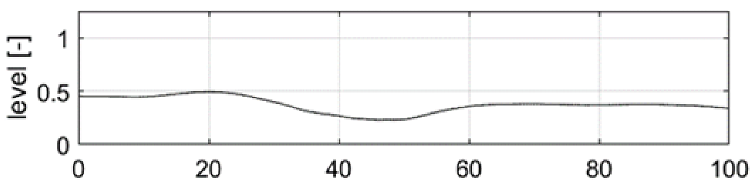

Fig. 9. Level of periodicity.

Taking into account these four indicators, a final evaluation of the road evenness is possible. The suggested limits result from two-dimensional vibration models for cars respectively trucks. The resulting vibrations of the vehicle's driver, the vehicle's cargo and the pavement loading caused by the irregular unevenness are analyzed. In this context, a linearity to SBL as well as DBL/4 can be observed (see equations 2 to 4). The identified correlations result in two construction contract related limits for irregular unevenness. The correlation between the unevenness and the effect of the vibration on the vehicle's passengers is decisive in this case. In order to restrict the impact on the drivers and their health SBL or DBL/4 > 4 mm (see Fig. 10, yellow section) is defined for monetary deductions, SBL or DBL/4 > 9 mm for structural defect rectifications (see Fig. 10, red section) [11].

$$wheel\ load\ increase\ \Delta F_{z,max} = 3.583 * \{SBL\}\ [\%] \tag{2}$$

$$cargo\ acceleration\ a_{z,max} = 0.275 * \{SBL\}\ \left[\frac{m}{s^2}\right] \tag{3}$$

$$driving\ comfort\ a_{wz,eff} = 0.038 * \{SBL\}\ \left[\frac{m}{s^2}\right] \tag{4}$$

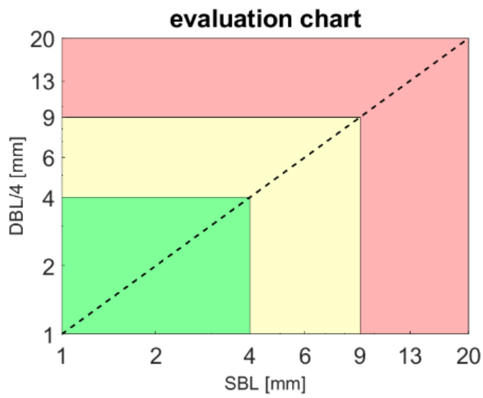

Fig. 10. Limit values of the WLP calculation.

Periodic unevenness causes stronger influences on driving comfort and pavement loading than irregular unevenness, which results in a lower limit for structural defect rectifications, depending on the level and the length of the periodicity. The calculation of the limit value is given by equation 5. $\alpha_{\text{length periodicity}}$ represents the weighting factor regarding the length of the periodic unevenness. For unevenness with a maximum length of 30 meters, $\alpha_{\text{length periodicity}} = 0$, whereas for periodic unevenness with lengths greater 120 meters $\alpha_{\text{length periodicity}} = 1$. Intermediate values are interpolated. $\alpha_{\text{level periodicity}}$ represents the weighting factor regarding the level of the periodic unevenness. The factor is zero for a maximum level of 0.5 and one for a level greater 0.65. Intermediate values are interpolated, too. The graphic display of the limit value progression is shown in Fig. 11 [11].

$$limit_{structural\ defect\ rectifications} = 9\ mm - \alpha_{length\ periodicity} * \alpha_{level\ periodicity} * (9-5)\ mm \tag{5}$$

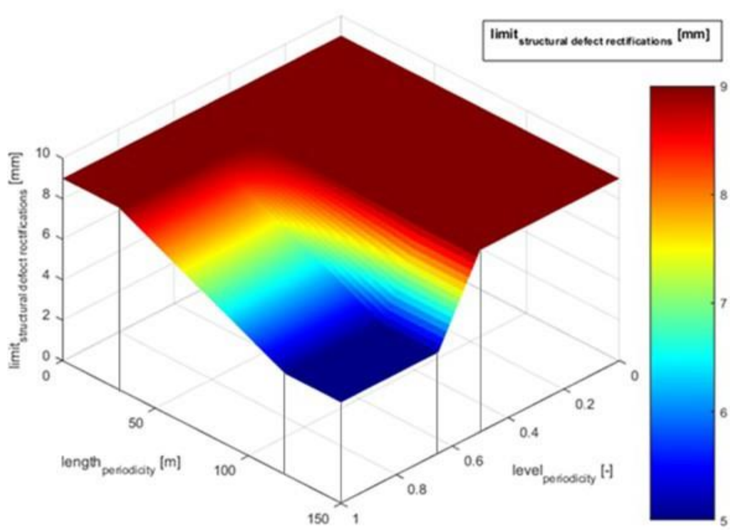

Fig. 11. Limit value progression for structural defect rectifications.

2.2 Practical examples of the WLP calculation

As mentioned before, the WLP calculation results in three records (WLP, SBL and DBL/4) generated from the longitudinal road profile. In addition, the level of the periodicity is shown. To enable a comparison with the current evaluation method of the rolling straight edge, a simulation of its measurement record is also displayed in the graph (see Fig. 12). Analogue to the evaluation process of the rolling straight edge, the profiles are segmented into sections, each two meters long. When evaluating the road's evenness, the maximum of SBL and DBL/4 is decisive. The corresponding value is assumed to be constant for the associated window [11].

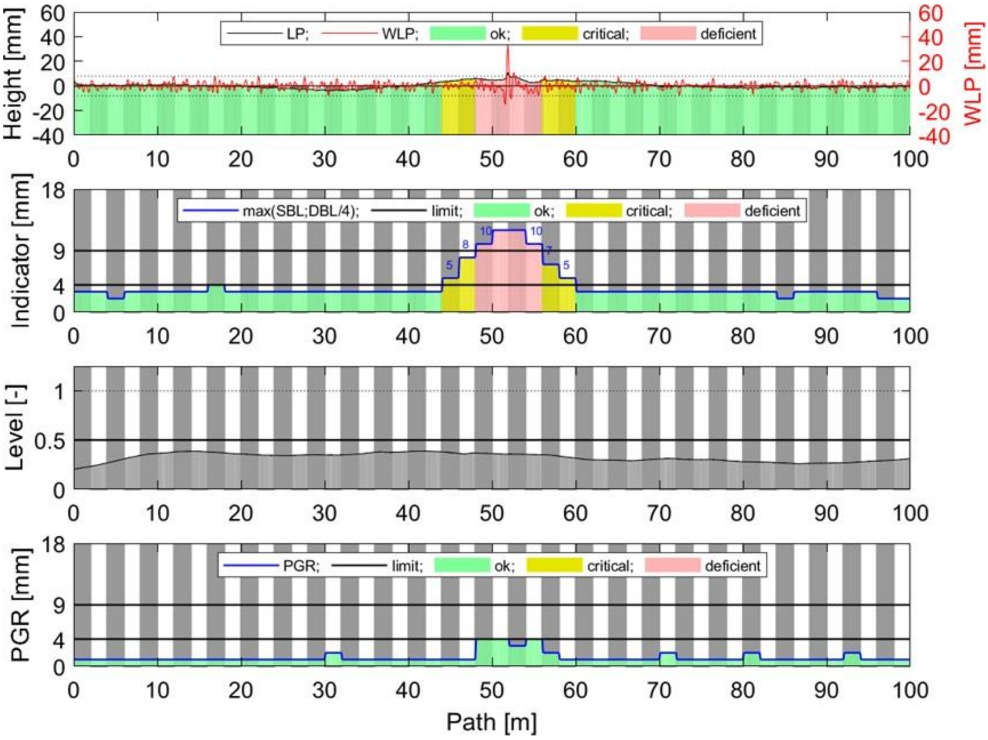

Fig. 12. Longitudinal road profile mainly characterized by irregular unevenness.

Fig. 12 gives an example of a single unevenness, identifiable by the amplitude deflection in the WLP profile. The decisive indicator exceeds the limit of nine millimetres, so that the related area of the road profile is classified as deficient. The adjoining areas are rated as critical. This labelling respectively the expansion of the individual unevenness results partly from the sliding displacement of the evaluation section and the weighting using a triangular window. There is no significant periodicity in the evaluated longitudinal road profile (see Fig. 12, third diagram), so that the profile predominantly reflects an irregular respectively stochastic unevenness. In comparison to the results of the WLP, the record resulting of the rolling straight edge simulation does not show a significant amplitude deflection. The entire measuring path is classified with a sufficient evenness. No limit value exceedance can be detected (see Fig. 12, fourth diagram).

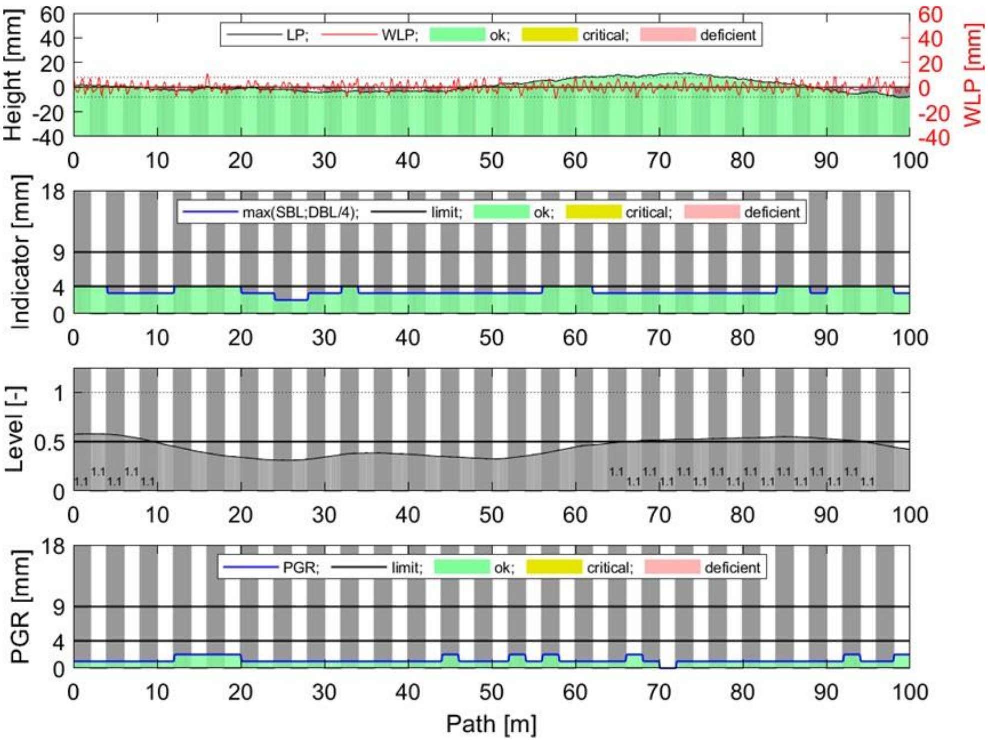

Fig. 13. Longitudinal road profile characterized by short-wave periodicities.

The second example (see Fig. 13) is characterized by short-wave periodicities with a wavelength of 1.1 meters. The level of periodicity is just above the cut-off value of 0.5. Furthermore, the periodicity extends only over a short distance. For this reason, the limit value for structural defect rectifications remains at 9 mm and is not reduced. The amplitude of the periodic unevenness is relatively low, so that the unevenness does not exceed the limiting values of 4 mm and 9 mm, respectively. Similar to this result, the rolling straight edge does not detect any significant unevenness.

The third example (see Fig. 14) is characterized by middle-wave periodicities with a wavelength of 5.1 meters over the entire evaluation section. Due to the length and the level of the periodic unevenness the limit value for structural defect rectifications is lowered to 5 mm. Overall, the amplitudes are relatively high, with the result that there are limit value exceedances detected in the WLP record. The unevenness resulting from the periodicity is mainly classified as critical. Two areas (12 to 16 meters and 82 to 96 meters) of the road profile are rated as deficient due to higher amplitudes of the periodicity. In contrast to this result, the rolling straight edge does not detect any significant unevenness. In this context, it should be taken into account that it is not possible to detect these periodicities of the road profile with the rolling straight edge due to its limited length. Although the example only includes middle-wave periodicities, the wavelength exceeds the device length of four meters.

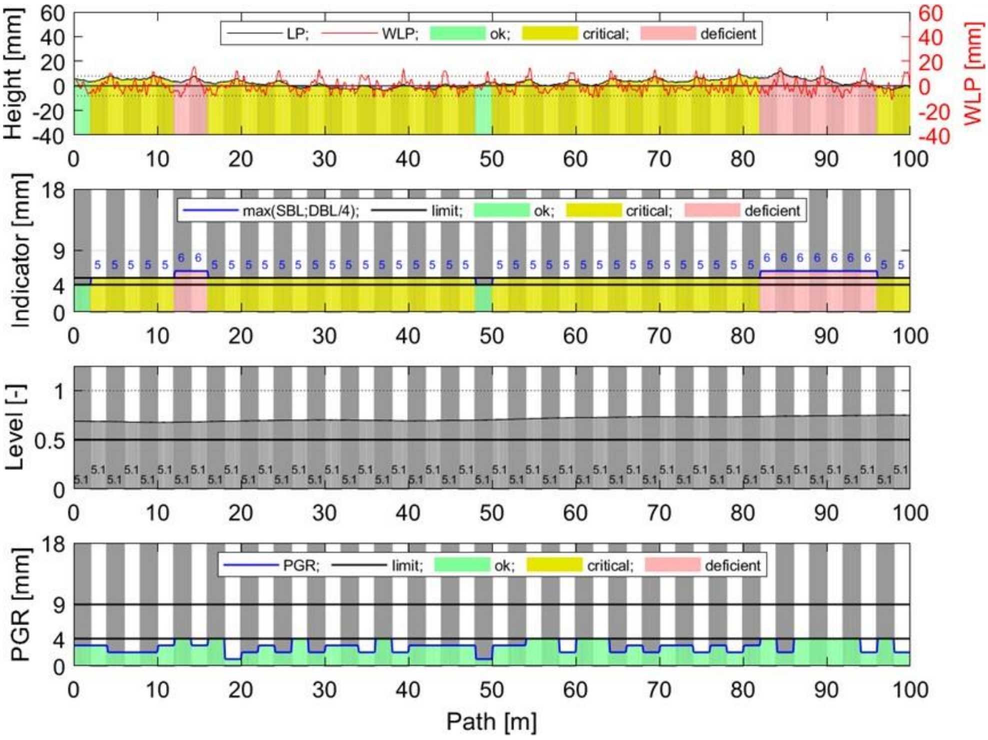

Fig. 14. Longitudinal road profile characterized by middle-wave periodicities.

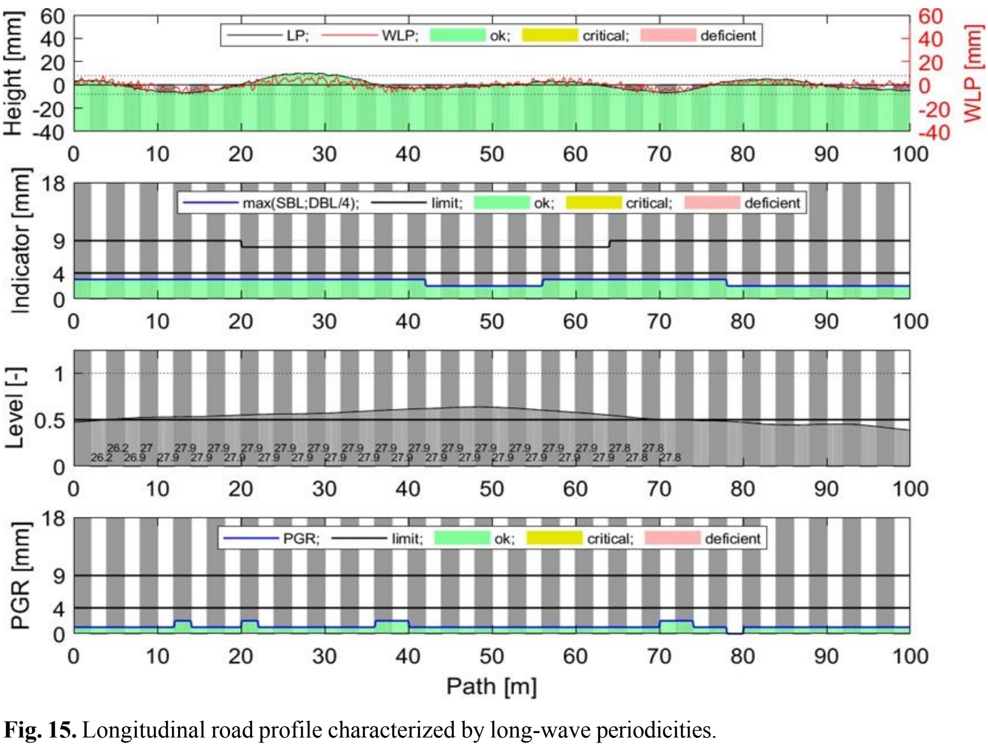

Fig. 15. Longitudinal road profile characterized by long-wave periodicities.

Likewise, long-wave unevenness cannot be detected by the rolling straight edge (see Fig. 15). Although the WLP evaluation recognizes these periodicities, there is also no limit value exceedance in the presented example. This result can be explained by the small amplitudes of the unevenness combined with the long wavelengths of the periodicities (26.2 m to 27.9 m) and its limited length of exposure.

3 Conclusion

The given examples exhibit significant differences regarding the results of the two measuring and evaluation procedures. Although the WLP identifies unevenness exceeding the limit value, there is no detection in the rolling straight edge profile. In addition, there is no evaluation procedure to identify periodicities included when using this device.

Consequently, the WLP has the advantages of a precise detection of unevenness, irregular, single and periodic. In addition, the combined effects of these different types of unevenness are assessed by adjusting the limit value for structural defect rectifications. Besides the evaluation methodology, there is another advantage related to the measuring method. Due to the utilization of high-speed road profilometers, interventions in road traffic can be minimized. Precise data of the longitudinal road profile can be recorded for the WLP-evaluation without large amounts of time and personnel resources.

The future implementation into the technical regulations will allow a widespread application of the WLP methodology in the context of the evaluation of road construction contracts. This will enable an optimized evaluation of the longitudinal road profile and associated with this a more durable road infrastructure and higher driving comfort for road users. After successful proving, an additional implementation in the regulations regarding the evaluation of the road condition as well as regulations regarding new construction of roads is conceivable.

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