PAVEMENT MONITORING: NEW METHODS FOR ANALYZING LONGITUDINAL EVENNESS

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ABSTRACT

The current method of analyzing longitudinal profile data in Germany (based on Power Spectral Density analysis) has been under criticism for some time now, the main reason being the inability to correctly characterize the unevenness in terms of its random, periodic and transient parts on a consistent basis. The paper deals with general approaches and basics in evaluating longitudinal profile data and then describes two new evaluation methods being capable of evaluating the whole range of wavelengths and shapes (irregular, periodic, transient) relevant to longitudinal evenness. Meanwhile both indicators have been included in the national monitoring program and first statistical results for the whole network of primary roads can be presented.

1. INTRODUCTION

In Germany pavement monitoring on primary roads includes the measurement and analysis of the longitudinal evenness based on longitudinal profiles. State-variables are calculated for sections of 100 meters which prove to be significant for pavement management. To rate the conditions these (physical) quantities are divided into classes ranging from 1 (very good) to 5 (very poor).

The index currently used of analyzing longitudinal profile data – the so-called “AUN” which is based on PSD analysis - is suited to quantify only the random unevenness and thus has been under criticism for some time now, the main reason being the inability to correctly characterize the unevenness in terms of its random, periodic and transient parts on a consistent basis. Graduated, usually periodic unevenness such as that occurring primarily on old concrete pavements of highways - many of these surfaces requiring renovation - as well as individual obstructions (transitions between pavements, bridge abutments etc.) are not considered adequately by the present evaluation technique.

In recent years two new methods of analyzing longitudinal evenness have been developed considering these characteristics along with their effects on drivers, vehicles and pavements. One of them is a response-type approach: three filters, applied to the pavement data, determine dynamic wheel loads (criteria: pavement loading and driving safety), human exposure to vertical vibration and vertical acceleration on the load area (criterion: cargo loading) respectively. The three filter outputs are normalized to make them comparable among each other and the highest output within a 100-m section is denoted “LWI” which stands for “Effective Longitudinal Evenness Index”.

The other one is a combination of a purely “geometric” and a response-type indicator called the “Weighted Longitudinal Profile”. The method consists of a weighting of the Fourier spectrum of the signal along with a subsequent partition in octave bands. The (inverse transformed) octave-band filtered signals in turn are summed up in a way that takes into account their respective power contributions to the total power of the weighted spectrum. So especially periodic components can be visualized and evaluated adequately.

2. EXISTING APPROACHES TO EVALUATE LONGITUDINAL EVENNESS

Existing approaches to the evaluation of longitudinal evenness may roughly be divided in equipment-specific methods and numerical methods based on measured longitudinal elevation profile, see figure 1. Equipment-specific methods include, for example, rolling straightedge, slopemeter and profilograph.

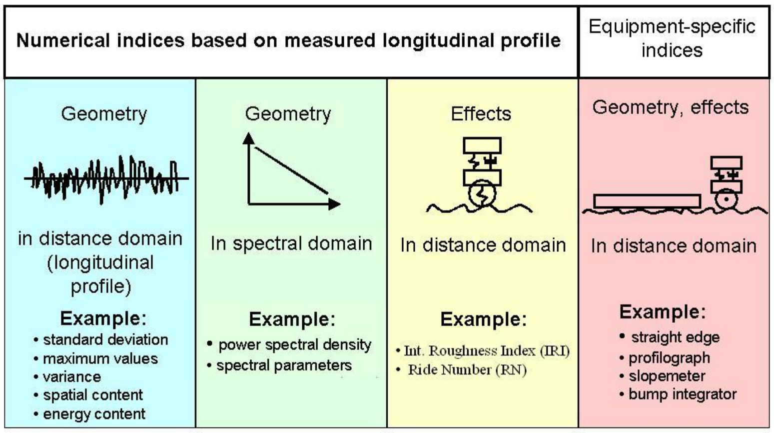

Figure 1 – Existing approaches for evaluating longitudinal evenness

For monitoring purposes on a net-wide level one prefers to measure the “true” longitudinal elevation profile using a non-contacting profilometer, followed by the calculation of suitable indicators of longitudinal evenness from the measured profile. These can be either “geometrical” indices calculated directly from the elevation profile or its 1st, 2nd [6,11,18] and even 3rd [26] derivatives respectively, like e. q. mean, median, standard deviation, root mean square, variance, range, etc., or indices inferred indirectly by means of e. q. wavelet decomposition [14,25,28] and Fourier transforms [2,5,10,20]. Besides that diverse filtering techniques (moving average, Butterworth, Chebyshev, etc.) are used to pre-process the profile data and to calculate unevenness indices with respect to different wave bands (e.q. short, medium and long waves).

The alternative is to deduce the dynamic response of measuring devices or vehicle components (axles, bodywork, seats, cargo load) and/or the perception of driver/passengers from the measured elevation profile by appropriate filters and to express the output in terms of indicators giving a statistical and/or peak rating for a given evaluation length (response-type indicators). Approaches of this kind include, amongst others, the International Roughness Index, IRI [21,24], the Half-Car Roughness Index, HRI [23], even a Full-Car Roughness Index [8] and the Ride Number, RN [3], which is defined as an exponential transform of the Profile Index (PI). The Profile Index, in turn, uses the same quarter car filter as the IRI, but with other coefficients. The Ride Number is a “comfort” number, scaled from 5 (perfectly smooth) to 0 (maximum possible roughness) and based on human rating experiments.

A more recent approach of human rating experiments uses fuzzy set theory [15]. The results were compared to IRI measurements. Another example of a response-type indicator is the dimensionless “Dynamic Evenness Index” LWI [24], which will be presented here.

One of the drawbacks of response-type indicators as compared to geometrical indicators is that they are linked to specific speeds and system properties, so that evaluation may not be sufficiently comprehensive or objective. It can, however, be argued that the point of interest for evaluation is not the geometrical shape of the road surface, but its dynamic effects. The advantage of the response type indicators is that they permit differentiated evaluation of longitudinal evenness with respect to irregular, periodic and local characteristics.

Some of the above mentioned evaluation approaches are used in a more academic environment, others are widely used in pavement monitoring practice on a national or even international level. Diverse national and international experiments have been conducted in the past in order to correlate and harmonize evenness measuring and evaluation methods, like the International Road Roughness Experiment, IRRE, [21], the European FILTER experiment [1] and the PIARC EVEN experiment [22]. A recent comparison between Profile Index, PI, and International Roughness Index, IRI, can be found in [26]. For a comparison of three widely used evenness evaluation methods in Europe, IRI, PSD and Wave Bands Analysis, see [9]. A rather comprehensive table of roughness devices and indicators has been put together in [4,19].

A second method presented in this paper is the so-called “Weighted Longitudinal Profile”. It is intended for road maintenance and acceptance inspection purposes and able to reconcile the above mentioned two opposing approaches – geometric and response-type - because it uses features of both. Both methods are presented in the following chapters.

3. THE DYNAMIC EVENNESS INDEX (LWI)

Pavement unevenness subjects vehicles to vertical vibrations. These vibrations act primarily on the vehicle's axles and bodies. The vibrations are transferred through the vehicle and via its seats to the occupants, or directly to goods being transported. This exerts corresponding loads on driver and payload. The vibrations also exert alternating forces on the pavement, thus subjecting the road to roughness induced wear. If the wheel load dynamics exceed a certain level, driving safety is affected due to the lack of road contact, especially on wet surfaces in bends. Accordingly, the Dynamic Evenness Index is based on the three following types of vibration (Figure 2):

- Dynamic wheel loads (criteria: pavement loading and driving safety)
- Human exposure to vertical vibration
- Vertical acceleration on the load area (criterion: cargo loading).

Figure 3 shows the calculation scheme for the LWI. It is to be read from the bottom upwards. The longitudinal road profile is rated through three different filters: A “human filter” representing how vibrations are perceived by the driver of a middle-class car travelling on the road at 100 km/h, a “payload filter” which determines the vertical acceleration acting directly on the loading area via the center axle of a three-axle semi-trailer travelling at 80 km/h on the road, and a “wheel-load filter” which calculates the wheel loads acting between the road and the tyres of the drive axle of an 11.5-t truck, also travelling at 80 km/h. All three filters have been selected so as to represent vibration levels typical for modern trucks and passenger cars.

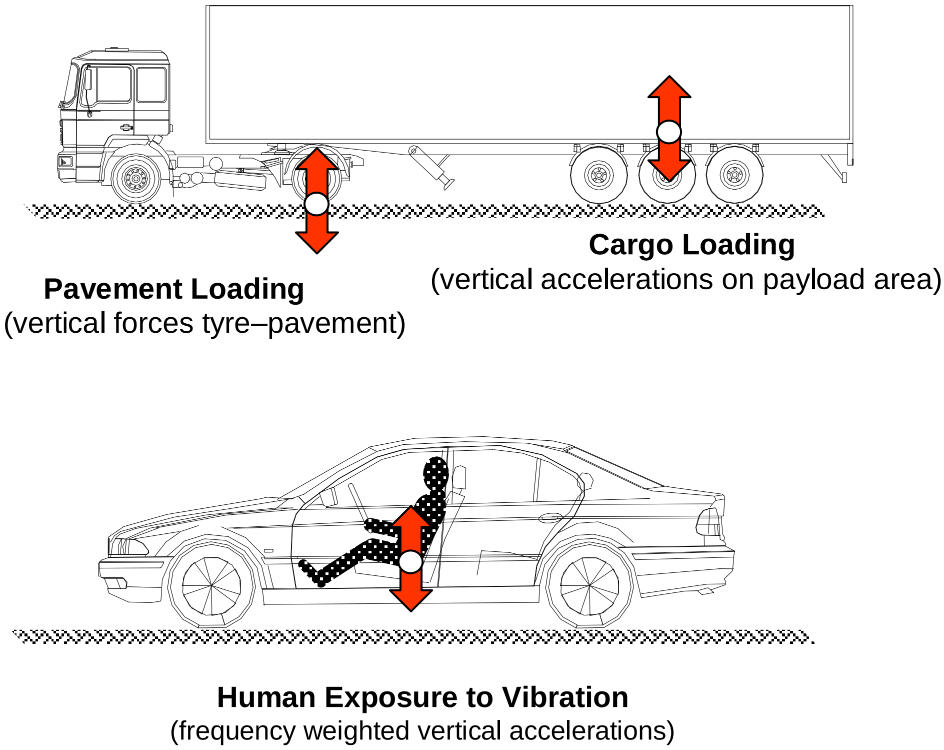

Figure 2 – Criteria for assessing longitudinal evenness, [24]

The “human filter” incorporates a typical middle-class car (VW Passat), typical seats and an internationally standardized (ISO 2631-1 and VDI 2057 [12, 13]), frequency-dependent human sensitivity to vibrations comprising vertical oscillations in the driver's seat. Simulations are performed not only of human perception of frequency-dependent vibrations, but also the possible effects of such vibrations on human health.

The three-axle semi-trailer selected as a basis for the “payload filter” also reproduces typical loads exerted on German federal trunk roads, articulated vehicles constituting the predominant type of vehicle used in long-distance freight traffic.

An 11.5-t truck driving axle was selected as a basis for the wheel-load filter. It is used on nearly all long-distance freight vehicles with a maximum total weight of more than 18 t and exerts the highest load on road pavements by virtue of its load-bearing capacity.

The response to each longitudinal road profile therefore consists of the three following filter responses as a function of the distance: Wheel-load fluctuations, vibrations exerted on human beings and payload acceleration. In the calculation scheme, these three functions are first squared to consider the effects in terms of energy. After that, they are each divided by a reference value representing the theoretical maximum which each of the three filters would supply for a good road as defined by a particular power density spectrum. This provides three squared, normalized, dimensionless filter responses as a function of the distance. Their joint maximum value based on sections 100-m long represents the LWI.

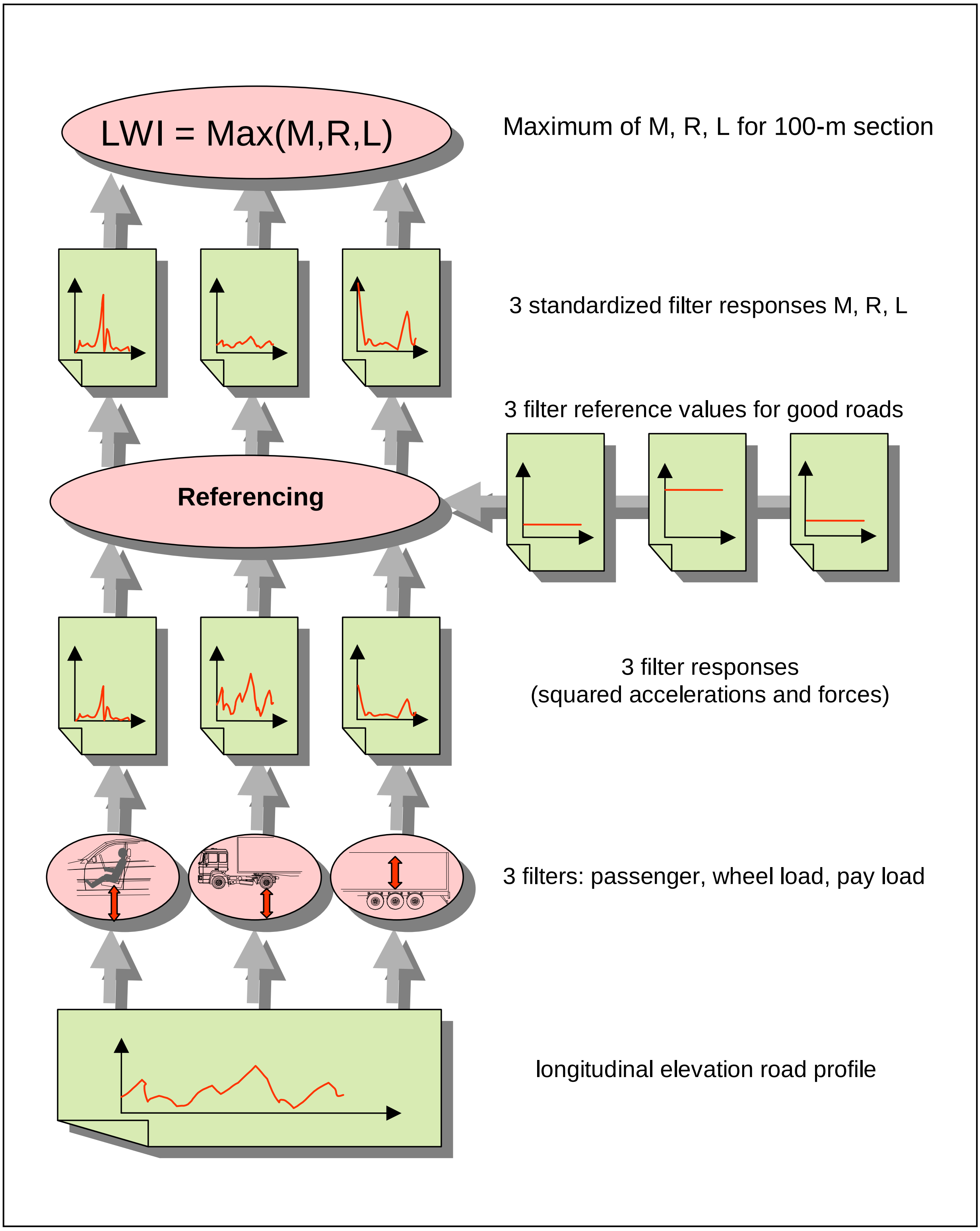

Figure 3 – Calculation scheme for the Dynamic Evenness Index (LWI), [24]

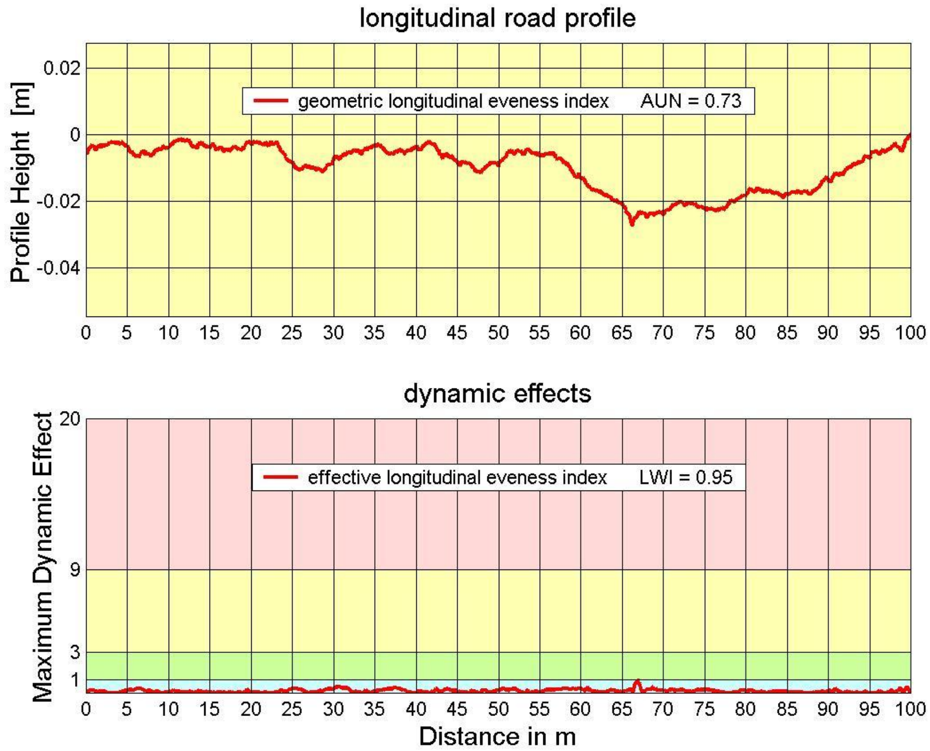

Figure 4 – LWI plot for a 100m section of a good road, LWI = 0.95, [24]

Figures 4 and 5 provide sample evaluations of two 100-m sections, one from a road exhibiting a high degree of evenness (Figure 4) and one from an old concrete pavement (Figure 5). In each case, the upper diagram shows the longitudinal elevation road profile, while the lower diagram shows the maxima of the three squared, normalized filter responses as a function of the distance. The calculation results in LWIs of 0.95 and 13.16 for a good road and poor road respectively.

Figure 6 shows how the LWI varies with pure random unevenness, expressed by “AUN” already mentioned in chapter 1 and waviness, “W”. AUN and W are descriptors of the “linearized” Power Spectral Density (PSD) in a log-log scale, where W denotes the slope and AUN the level of the PSD. W usually is between 2 and 3 (2.2 is a typical number for concrete and 2.5 for asphalt roads). Evidently, there is a linear relationship between AUN and LWI. AUN and LWI give equal results for random unevenness characterized by a waviness of 2. At other waviness factors LWI is larger and can become up to twice as large as AUN. This is because LWI is normalized to an average waviness factor of 2, and higher waviness factors (according to long waves with high amplitudes) exert larger forces on the payload whereas lower waviness factors (short waves of a larger amplitude) exert stronger forces on the road (in terms of higher wheel-load fluctuations). However, the greater the deviation between the actual power density spectrum and its representation through AUN and W, the greater the deviation in the mentioned relationship between AUN and LWI. Accordingly, the LWI can occasionally be lower than the AUN in spite of its general tendency to be somewhat higher.

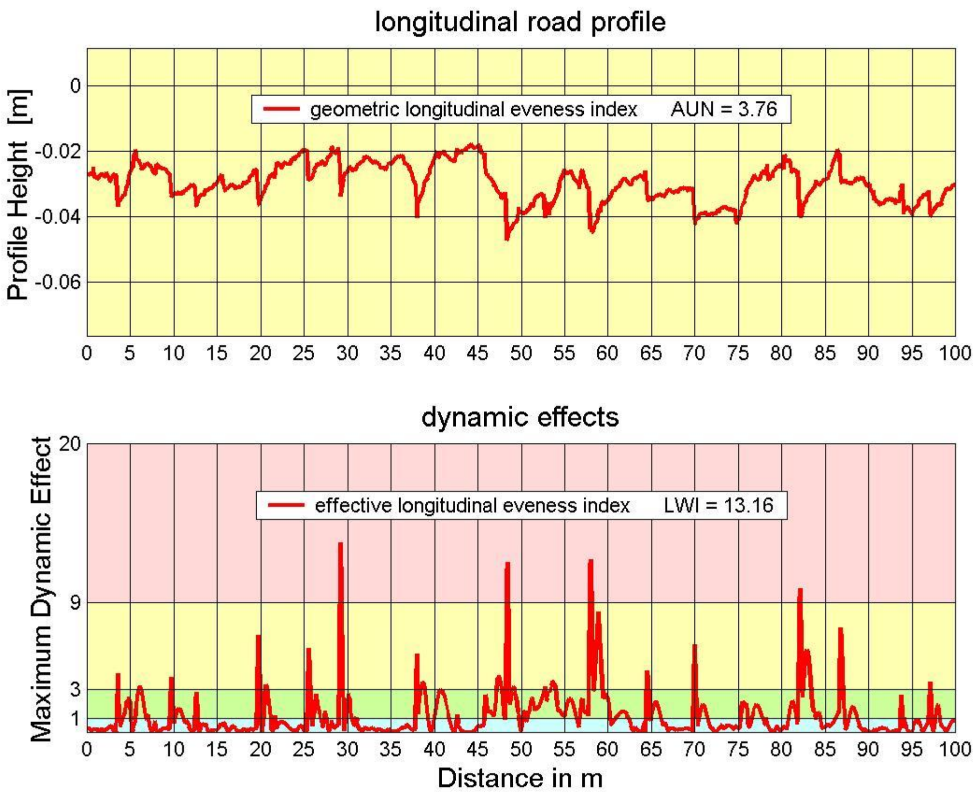

Figure 5 – LWI plot for a 100m section of a bad road, LWI = 13.16, [24]

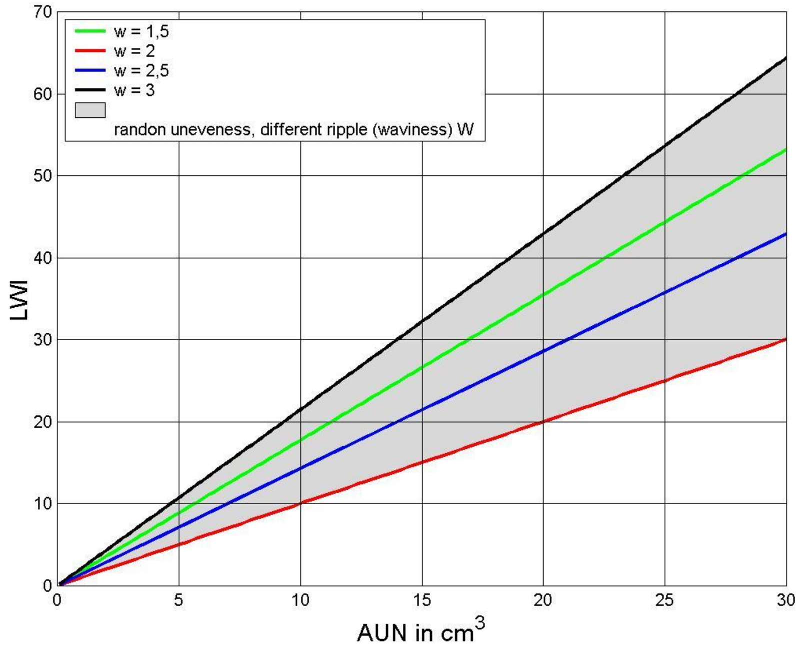

Figure 6 – Response of LWI to random unevenness, expressed by AUN and W, [24]

Following limiting values are recommended for trunk roads: “target value” LWI=1, “warning value” LWI=3 and “threshold value” LWI=9. Table 1 shows the forces and accelerations underlying these limits.

If the wheel-load fluctuation is decisive for the LWI, the threshold value implies a short-time, 50 percent reduction in wheel load, i.e. in forces which can be transmitted to the road (longitudinal and lateral). This can result in critical driving situations on bends with slippery spots. With respect to the road pavement, this limiting value implies a short-time 50 percent increase in wheel load and, accordingly, a five-fold rise in pavement damaging exerted on particularly exposed road sections, such as steps, if the "fourth power law" is used as a basis here.

If the payload acceleration is decisive for the LWI, an attainment of the threshold value implies a payload acceleration of up to 3 m/s^2. According to DIN 30786 [27], roughly 90% of the peak forces exerted on the payloads of semi-trailers lie below this value. This standard refers to the "worst case, i.e. a concurrence of unfavorable circumstances (for instance, transported load, condition of the carriageway and vehicle, speed of the vehicle)", quotation [27]. The freight tariff regulations of the German Railways [28] specify a vertical force component of 3 m/s^2 as a standard value for freight safeguarding. DIN EN 22247 [29] specifies acceleration amplitudes between 5 and 11 m/s^2 for vertical oscillation tests on packaged items ready for shipment.

If the vibrations exerted on the human body are decisive for the LWI, the threshold value means that seated persons are subjected to a frequency-weighted acceleration (root mean square) of up to 0.9 m/s^2 over 100 m. According to ISO 2631-1, [11], occupants of vehicles perceive this load to be "extremely noticeable". In comparison: 0.1 m/s^2 is "noticeable" and 0.3 m/s^2 "very noticeable". An 8-hour journey on a road whose evenness corresponds to the target value (0.3 m/s^2) takes the driver to the limits of his/her performance. Theoretically, it must be assumed that drivers incur a potential health risk if exposed to the warning value (0.5 m/s^2) and a substantial health risk if exposed to the threshold value (0.9 m/s^2) over a period of 8 hours in either case [11].

The mentioned limiting values have been established specially for the purpose of rating federal roads and motorways. Limiting values twice as high are applicable to municipal roads (half the speed limit), if the same vibration effects are used as a basis.

Table 1 – Recommended limiting values for the LWI and the corresponding effects of forces exerted on road, payload and human body

	Forces exerted on the road Driving safety	Payload acceleration	Forces exerted on the human body
LWI	**Maximum increase / decrease in wheel load** (with respect to static wheel load) **%**	**Maximum vertical acceleration** on the loading area **m/s^2**	**Effective value** of the frequency-weighted **vertical acceleration** **m/s^2**
1	17.5	1	0.3
3	30	1.7	0.5
9	52.5	3	0.9

In figures 7 and 8 AUN and LWI ratings for a collective of measured road surfaces are shown in comparison. The collective termed "good evenness" contained all sections which received AUN-based grades better than 2; these sections comprised 832 km of concrete road and 863.8 km of asphalt road. The collective termed "reasonable evenness" contained all sections which received AUN-based grades between 2 and 4.5; these sections comprised 229.5 km of concrete road and 143.8 km of asphalt road. A closer look to the results showed that the more stringent rating of the LWI with respect to the AUN followed from the fact that the LWI “detected” and assessed locations of single and periodic unevenness which the AUN was not able to detect.

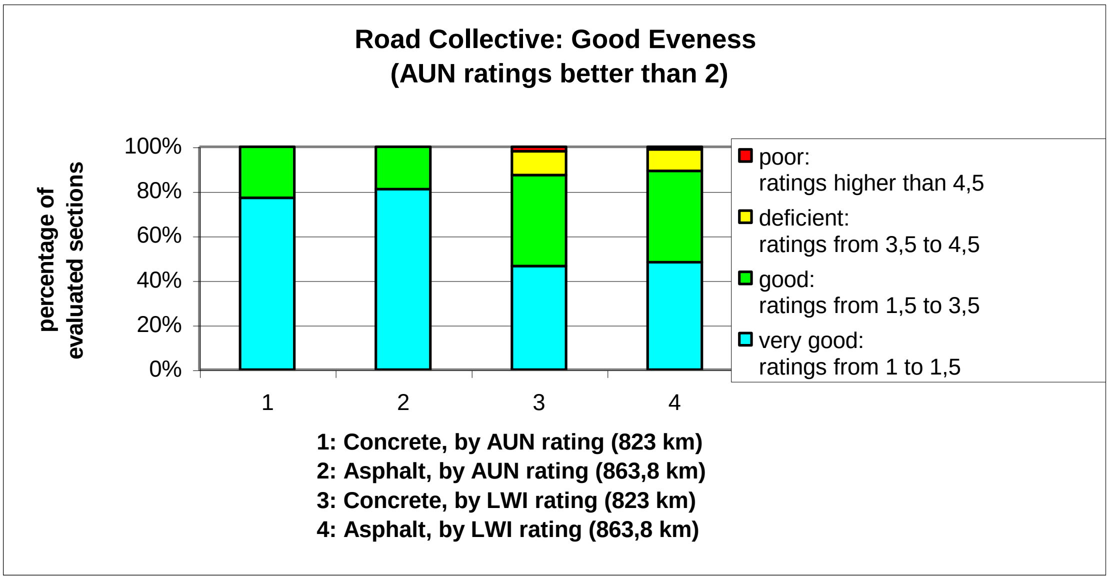

Figure 7 – Comparison of AUN and LWI ratings, collective “good evenness”

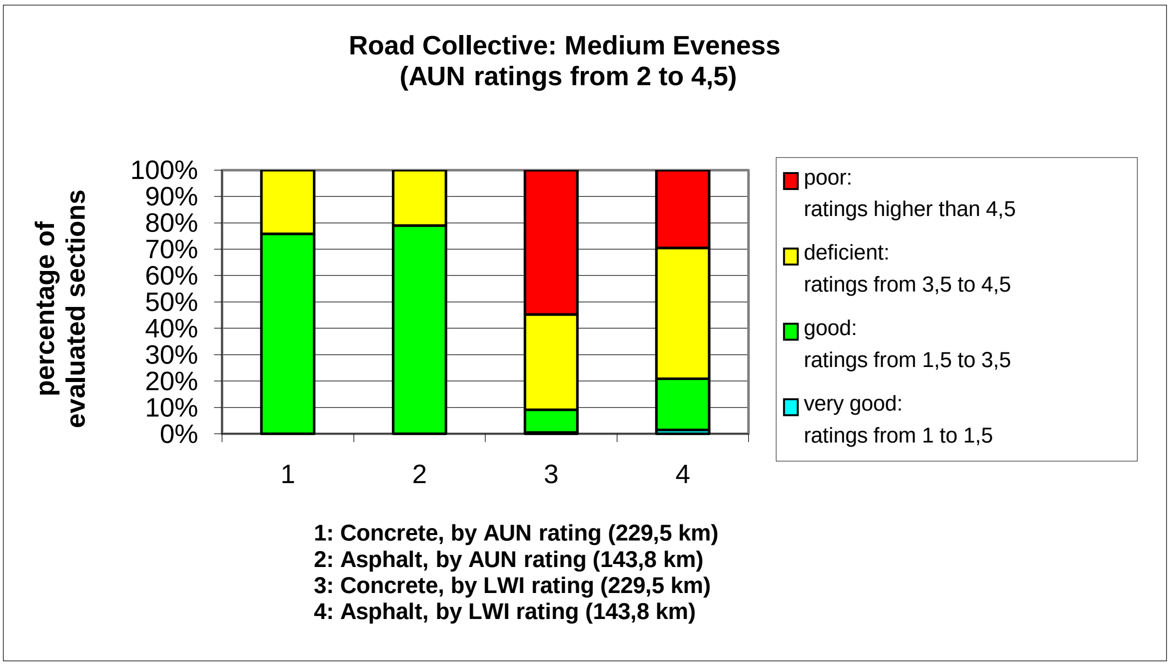

Figure 8 – Comparison of AUN and LWI ratings, collective “reasonable evenness”

4. THE WEIGHTED LONGITUDINAL PROFILE (WLP)

The "Weighted Longitudinal Profile" (WLP) is a combination of a purely "geometric" and a response-type indicator. The method consists of a weighting of the Fourier spectrum of the signal along with a subsequent partition in octave bands. The (inverse transformed) octave-band filtered signals in turn are summed up in a way that takes into account their respective power contributions to the total power of the weighted spectrum. By doing so, not only random but also single and periodic components of the longitudinal profile can be visualized and evaluated adequately. In the following the calculation scheme in terms of 4 calculation steps is explained.

Step 1: Transformation to spectral domain and dividing by reference spectrum

In a first step the longitudinal profile is transformed to spectral domain by a Fourier Transformation (FT). Afterwards, the Fourier spectrum, to be more precise, the amplitude spectrum, is divided by a reference spectrum which, in terms of PSD, corresponds to an AUN=1cm^3 and a waviness W=2.5. The procedure is shown in figure 9.

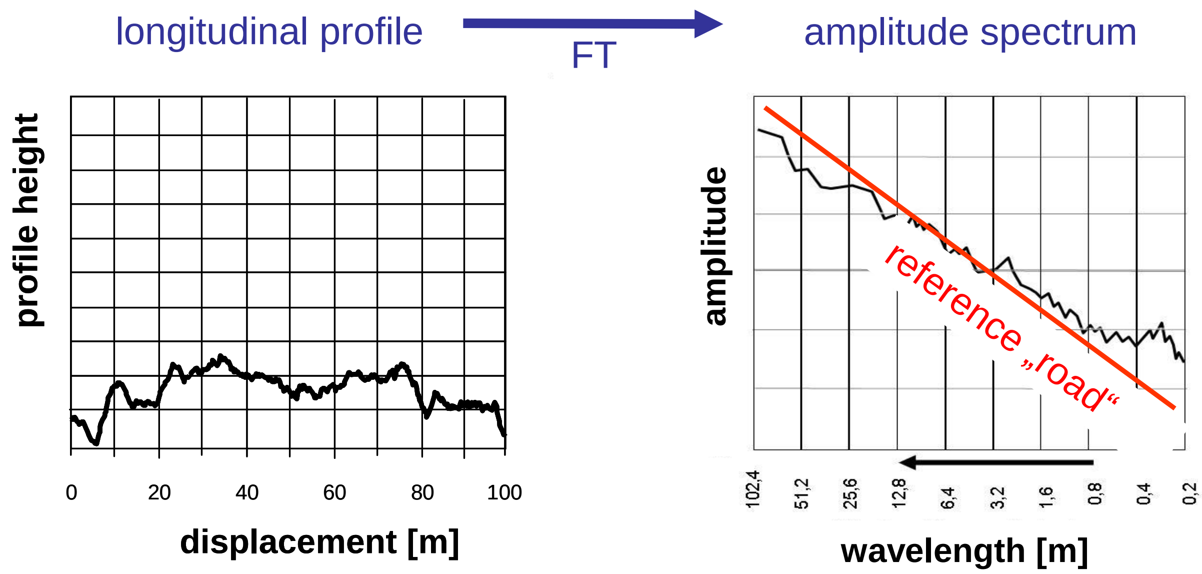

Figure 9 – Calculation step 1: Fourier transformation and "referencing" to the reference spectrum

Step 2: Octave-band filtering of the "referenced" spectrum

As a second step the "referenced" (divided) profile spectrum is "scanned" completely by an octave-band filter, since human perception and vehicle dynamics resemble an octave-band filtering covering only certain wavelengths according to the driven speed.

"Scanning" in this context just means the "splitting" of the spectrum into 9 octaves like shown on the right-hand sides of figures 9 and 10. Figure 10 is supposed to clarify the filtering effect: let's say a car is moving with a speed of 60 km/h. At 60 km/h the body of the car is most sensitive to wavelengths between 6.4 and 12.8 m. This sensitivity range would move towards longer wavelengths between 12.8 and 25.6 m, if the driver would double the speed, and towards shorter wavelengths (between 3.2 and 6.4 m) if the driver would half the speed (see figure 10).

Note: The octave-band filtering is included in the calculation scheme of the WLP in order to account for the effects of vehicle dynamics in the evaluation of longitudinal evenness.

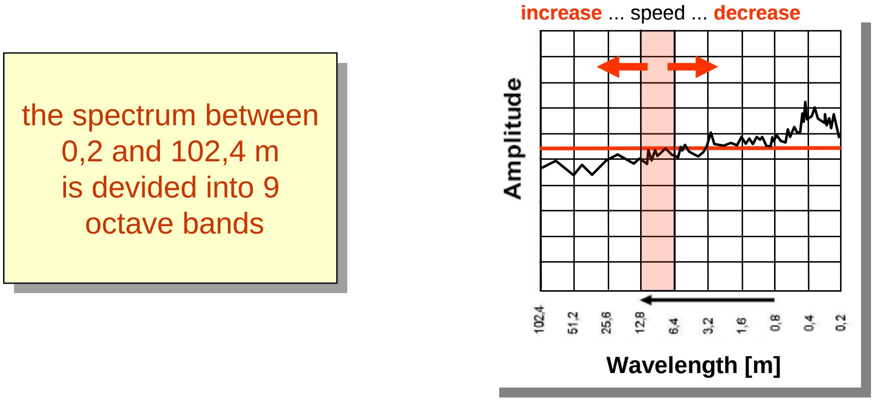

Figure 10 – Calculation step 2: Dividing the Fourier transform into octave-bands.

Step 3: Inverse Fourier transformation and assembling of the octave-band filtered signals

As a third step the octave-band filtering is performed by transforming each of the nine octave-bands back to space domain (inverse Fourier transform iFT) giving 9 octave-band filtered profiles. These 9 profiles are assembled now (added up) to give the Weighted Longitudinal Profile (WLP), but the crucial thing is that they are assembled according to their respective power contribution to the total power of the WLP.

This is simply done by multiplying the 9 octave-band filtered signals by 9 "weighting factors" before adding them up. The weighting factors are easily calculated by dividing the standard deviation of the respective signal by the standard deviation of the sum of the 9 signals, like shown in figure 11.

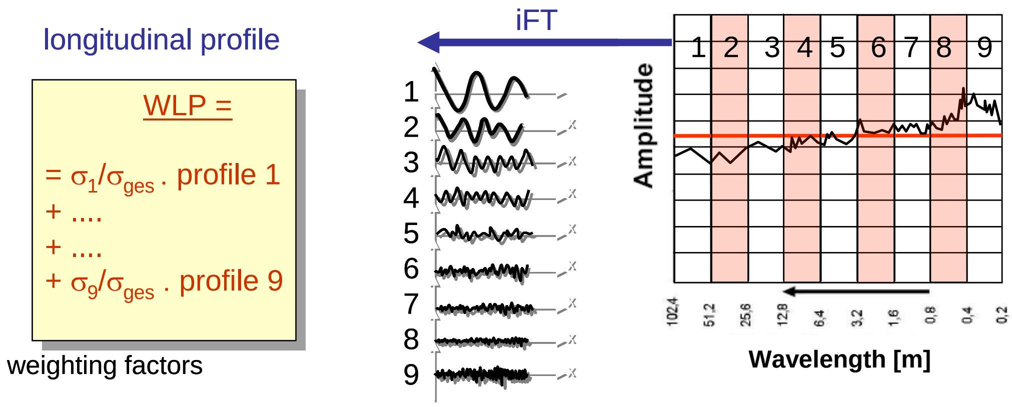

Figure 11 – Calculation step 3: Inverse Fourier Transformation and assembling the octave-band filtered signals.

Step 4: Calculation of the standard deviation and the range of variation of the WLP

As a result of calculation step 3 we have got the WLP for, in our example, an evaluation length of 100 meters (to be precise: 102.4 m). The WLP is now evaluated in terms of 2 indicators: its standard deviation, σWLP, and its range of variation, ΔWLP, based on the given evaluation length (see figure 12). σWLP is a measure adapted for irregular unevenness, while ΔWLP is suitable for transient occurrences. The ratio σWLP/σWLP is an indicator for the unevenness characteristic of the road section. Ratios of about 3 are an indication of a “wavy”, possibly periodic unevenness. Irregular unevenness exhibits typically ratios of about 6 and transients (e.g. single obstacles like bumps and potholes) cause ratios considerably higher than 6.

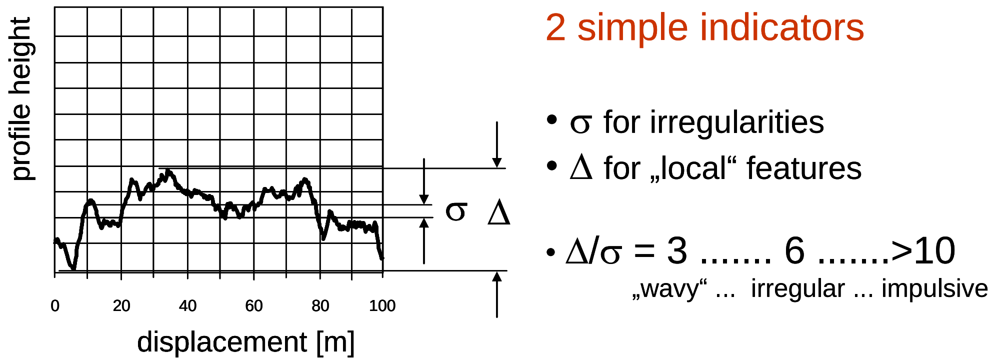

Figure 12 - standard deviation and range as indicators of the Weighted Longitudinal Profile

The following sample evaluations are taken from pavement monitoring applications. The two indicators mentioned above are grouped into four different classes ranging from “blue” (= good, i.e. better than a target value), “green” (= acceptable, i.e. between the target and a warning value), “yellow” (= defective, i.e. between the warning value and a threshold value) and “red”, which indicates a very poor evenness above the threshold value.

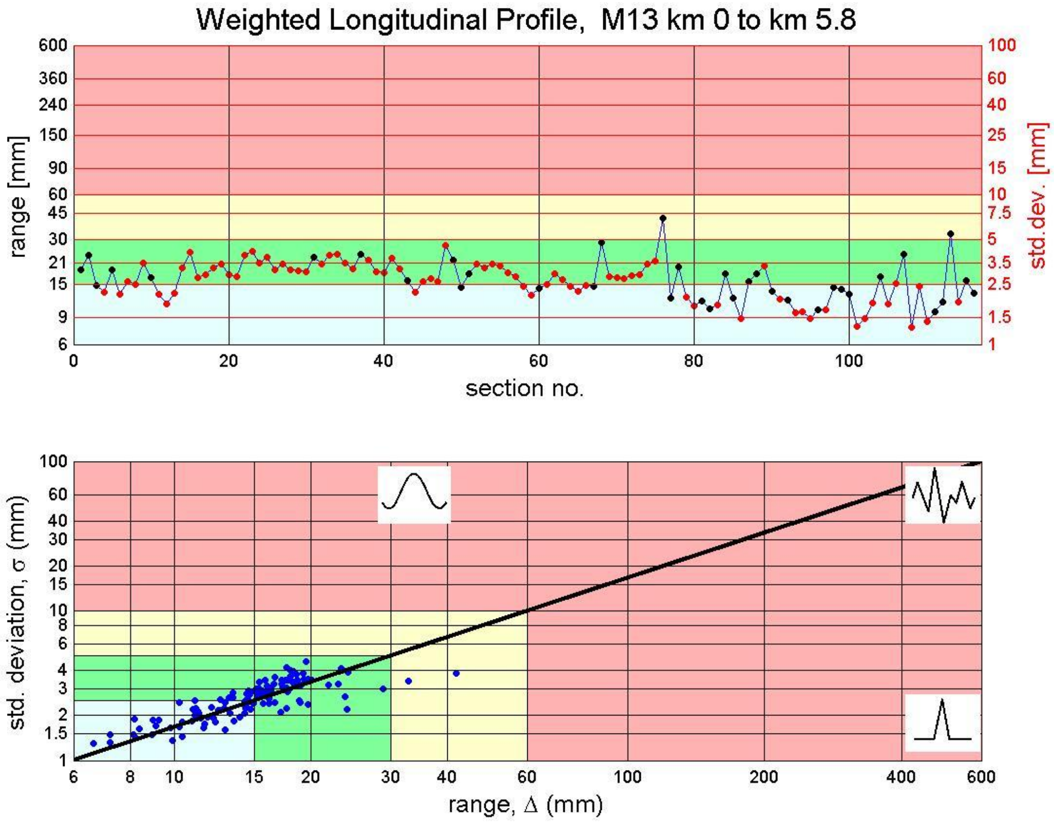

Figure 13 – road, 5.8 km long, with evenness mostly between target and warning value

Figure 13 shows the evaluation result for a 5.8 km long part of a road with unevenness mainly between target and warning value (green coloured area), especially in the first 80 sections. The sections above section 80 are more even in average. The upper graph in figure 6 shows the ratings along the road. A black dot means that the *range* was decisive for the rating of that very section and the scale to the left applies. Likewise, a red dot means that the *standard deviation* was decisive for the rating of that very section and the scale to the right of the graph applies.

The lower graph in figure 13 shows the results of each section in terms of the 2 indicators, standard deviation and range of variation. Only 2 of the 116 sections are above the warning level, see yellow coloured area. Dots considerable below the diagonal imply that the respective sections are dominated by a transient character, while dots considerable above the diagonal indicate that the respective sections have a “wavy” and potentially periodic character. Dots “along” the diagonal, however, are an indication of an irregular character.

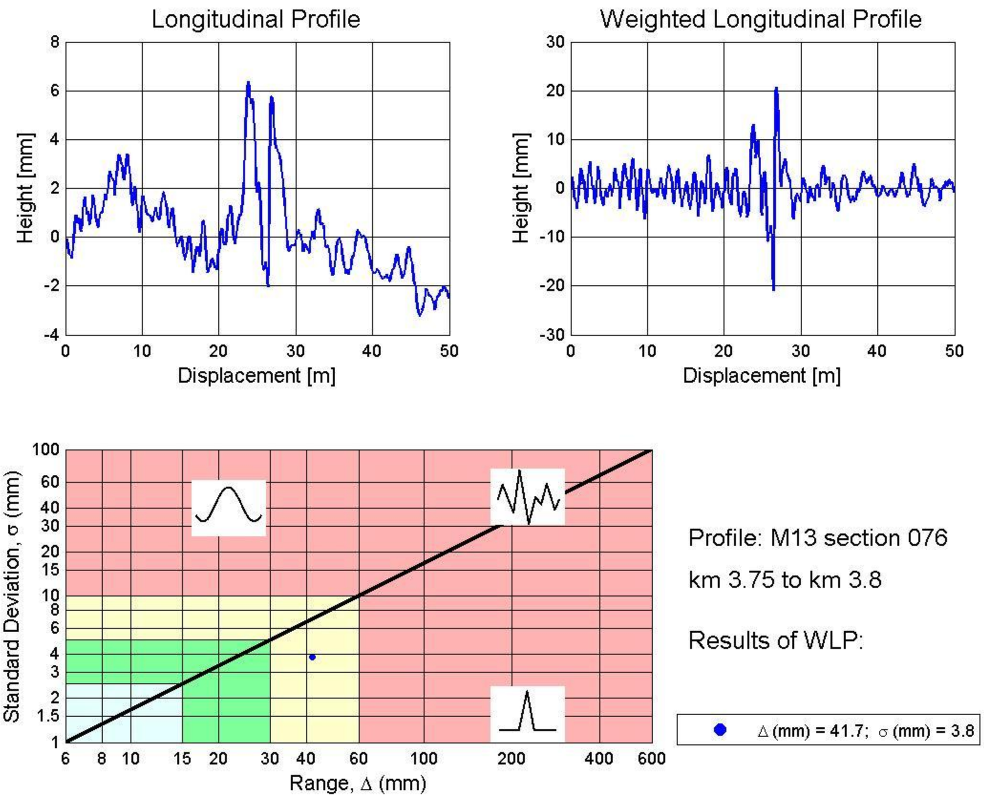

Figure 14 – detail of the road shown in figure 6: section 76 (section of highest unevenness)

Figure 14 lets us take a closer look to the section with the highest unevenness, which in this case is section 76. The lower graph in figure 14 conforms to the lower graph in figure 13 which we just explained. The upper part exhibits 2 graphs, the original (measured) profile on the left and the Weighted Longitudinal Profile on the right-hand side (note the different ordinate scaling). The transient can be found right in the middle of the section. Here we can see one feature of the Weighted Longitudinal Profile: it amplifies transients, brings them out of their surrounding environment; compare the height of the transient in the WLP with that one in the original profile; we find an amplification factor of 40/8 = 5. The part before the transient exhibits a periodicity with a wavelength of about 1.2 meters, whereas the part behind the transient exhibits a rather irregular character. Decisive for the rating of this particular section is the transient though.

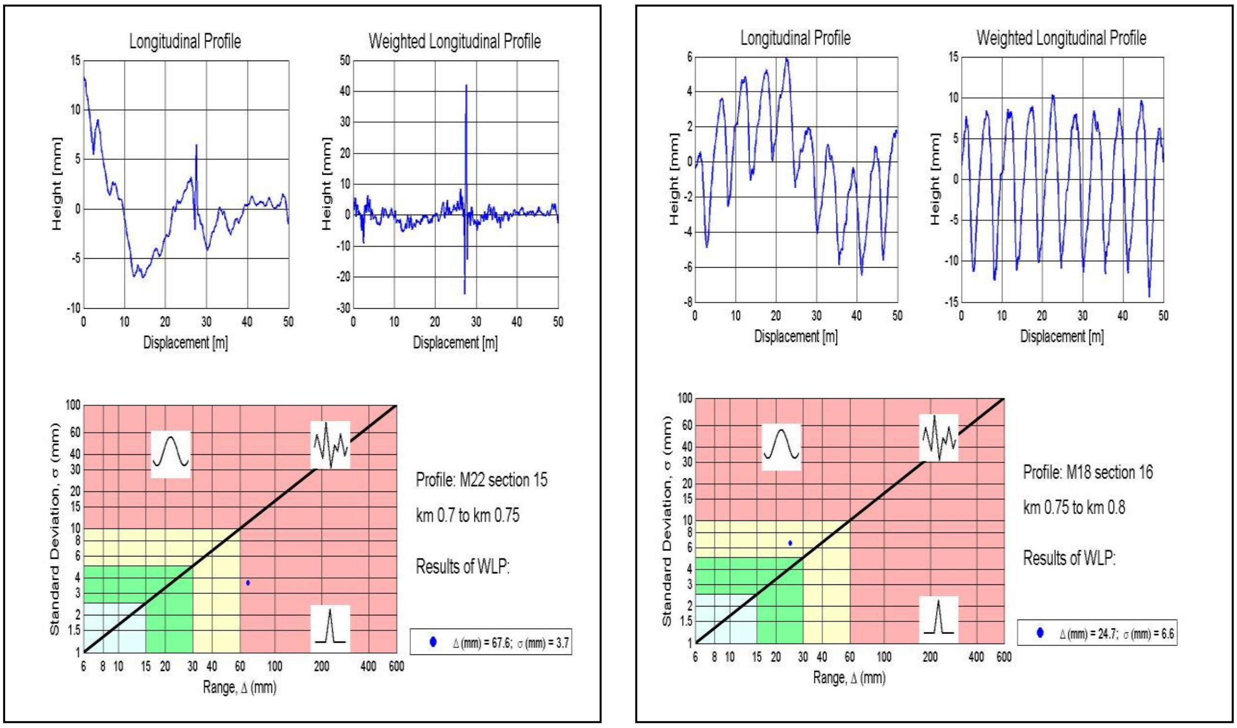

Figure 15 – WLP example for a transient and a periodic component

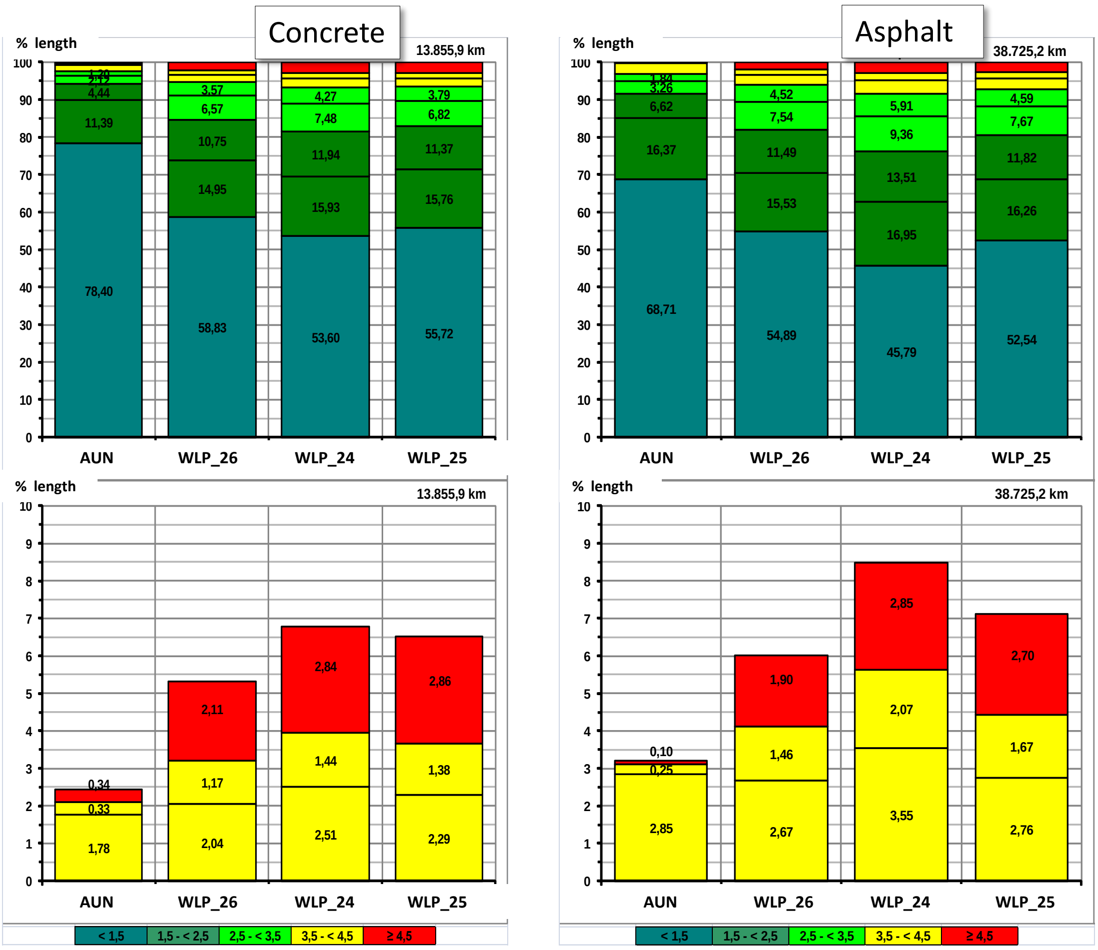

Figure 16 – WLP statistics for the German federal road network

Further obvious examples of a transient and a periodicity are given in figures 15.

Finally, figure 16 depicts the WLP assessment for the whole German federal road network in comparison with AUN ratings. The results for concrete pavements are shown on the left side, the results for asphalt pavements on the right side of the figure. The upper part of the figure contains the entire grading while the lower part is only an enlargement of the fraction that contains grades below 3.5 which marks the warning level. You find 4 columns – the left one represents the result for the AUN and the other 3 columns represent the results for 3 different versions of the WLP which differ only by an internal parameter called "waviness". The waviness controls the internal "weighting" of the large and small wavelengths. As you can see, the rating of the WLP is more stringent than the one of the AUN which is due to the fact that WLP – unlike AUN - represents not only an average but is able to detect and assess periodic and single features in the longitudinal profile as well.

5. CONCLUSION AND PROSPECT

Two new methods of assessing longitudinal evenness have been presented: one response-type indicator (LWI) and one, which is a combination of a geometrical and response-type indicator. Both are capable of detecting and evaluating all three phenomena of longitudinal evenness: irregular, periodic and transient unevenness. The first one distinguishes itself by the fact that it combines axle, cargo and passengers loading and hence extends sensitivity to the whole wavelength range relevant to longitudinal evenness, and the second stands out by the fact that it is a combination of geometric and response-type indicator and hence combines the advantages of the response-type methods (implicit evaluation of the shape and size of unevenness with respect to vehicle dynamics) with those of purely geometrical methods of evaluation (objectivity, without restriction of vibration properties and speed).

Investigations on a network level proved that both indicators are capable of assessing longitudinal evenness. In comparison with the previous indicator, AUN, a more comprehensive evaluation of longitudinal evenness including single and periodic features is possible. This results in a more stringent rating of the evenness in comparison with the AUN.

LWI already proved very helpful in allocation, visualization and interpretation of measured data. WLP is intended not only for pavement management but also for contracting purposes in the future in Germany.

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