

A ROUTINE MONITORING METHOD USING WEIGHTED LONGITUDINAL PROFILE

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ABSTRACT

Weighted Longitudinal Profile (WLP) which is a new index for characterizing longitudinal evenness was introduced in SURF 2008. As a result of sensitivity analysis of the WLP method using longitudinal profile data from the Japanese motorways, each of road surface distress showed its own identical tendency in a relationship between Δ WLP and σ WLP. Moreover, since data sites with larger Δ WLP of bridge joint tend to emerge upward in the relation between profile variation Δ and standard deviation of profile σ in octave bands #3 and #4, both octave bands are considered to give critical values to the original surface profile.

Because a laser profiler and a mobile profiling system, named STAMPER showed a similar slope of regression between Δ and σ , STAMPER can be used as alternative of laser profiler. By driving a STAMPER-equipped rent-a-car for 5 days on Autobahn, it was observed that IRI is distributed quite similarly between Autobahn and NEXCO motorways. It was also found that octave bands #5 and #6 are prevailing when profile variation Δ is low, or road surface is less deteriorated.

Finally if STAMPER can be used routinely and WLP is calculated for surface distress type, this will be an innovative monitoring method.

1. INTRODUCTION

It is not easy for road operators to objectively classify the type and severity of road surface disorder and proceed for appropriate budget allocation for the remedy. Since road profile is related to the disorder, waveband analysis of the profile, if easily done, must be quite useful for functional evaluation of pavement.

Another difficulty is that road profile cannot be measured frequently, because of the high cost of road surface measurement using a laser profiler. If this measurement can be done inexpensively, road surface control will be upgraded. However, if this is realized, an easier understanding of waveband still remains to solve.

This paper introduces the findings of a 5 years joint study to deal with the above problems between Federal Highway Research Institute of Germany and NEXCO Research Institute

of Japan. The two institutes are respectively in charge of control of technical standards of Autobahn and the Japanese motorways.

2. WEIGHTED LONGITUDINAL PROFILE

The *Weighted Longitudinal Profile* (WLP) is a new index for characterizing longitudinal evenness and was developed by Ueckermann in 2004 and presented by Maurer et al. in SURF 2008 [1]. The calculation scheme is shown in Figure 1. The WLP is based on the (measured) longitudinal profile of the road (upper left graph). As a first step this profile is Fourier-transformed to give the spectrum of the road (black curve in the upper right graph). In a second step the spectrum is “divided” by a “reference” spectrum (red line). The reference spectrum represents a spectral evenness characteristic which is typical for an average road profile. The result is a “weighted” spectrum which is shown in the figure at the bottom right graph.

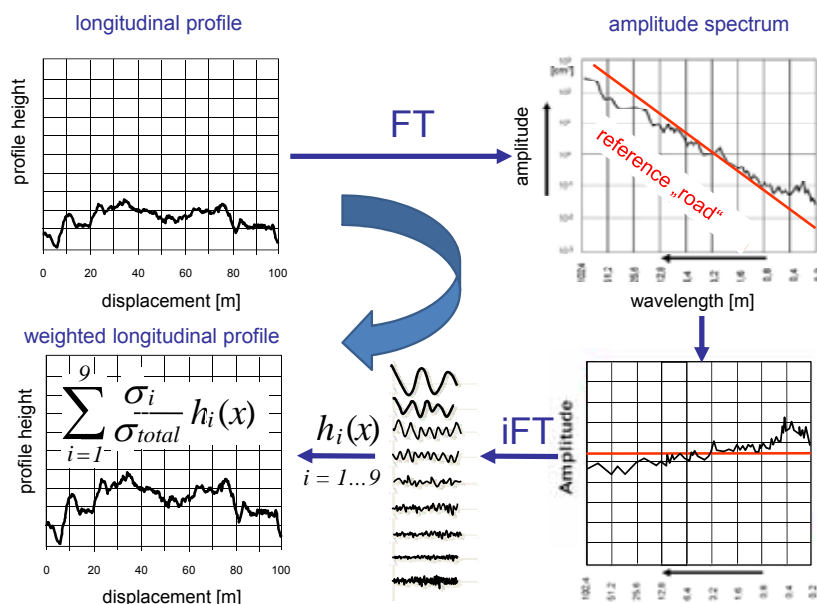


Figure 1 - Calculation scheme for the Weighted Longitudinal Profile (WLP)

The weighted spectrum is split into 9 octaves covering all wavelengths between 0.2 and 102.4 meters. Each of the octaves is then transferred back into the spatial domain giving 9 octave-band filtered signals $h_i(x)$ as shown in the middle of the bottom of the figure. These 9 signals, finally, are summed up provided with pre-factors to give the WLP (bottom left graph). The pre-factors take into account the respective power contribution of each signal to the sum of the 9 signals, expressed by the ratio $\sigma_i / \sigma_{total}$ (= standard deviation of signal i divided by standard deviation of the sum of the 9 signals).

To conform to the international definition of longitudinal evenness the WLP is filtered by a band-pass filter (Butterworth 4th order) to contain only wavelengths between 0.5 and 50 meters.

The WLP is characterized by two indicators:

- Standard deviation (σ_{WLP}), and
- Range of variation (Δ_{WLP}) which is the difference between the maximum and minimum value in the examined road segment (here: of length 50 m).

In the following four figures evaluation examples are given for three unevenness patterns (Fig. 2), focussing onto an irregular unevenness (Fig. 3), transient (impulsive) occurrences in a profile (Fig. 4) and a “wavy” unevenness characteristic (Fig. 5).

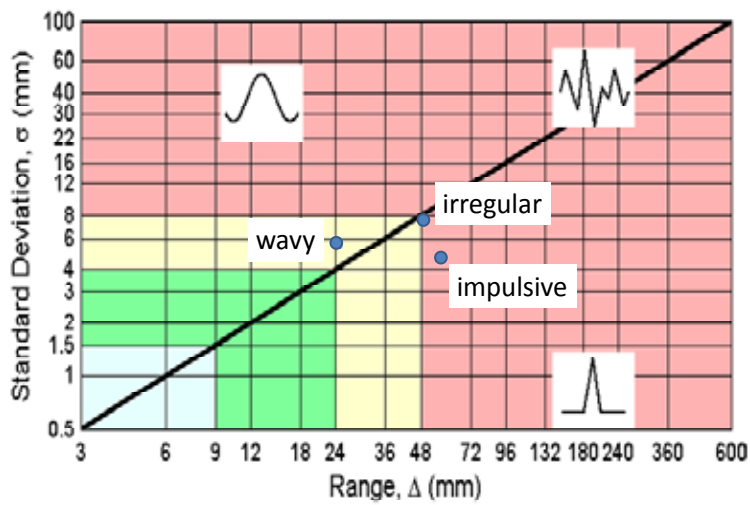


Figure 2 - Evaluation example of an irregular, transient and wavy unevenness patterns

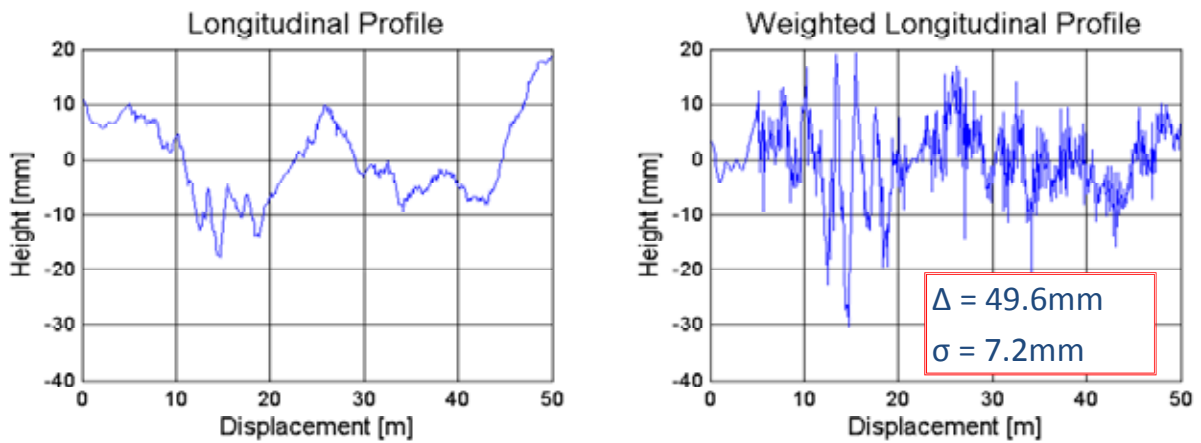


Figure 3 - Evaluation example of an irregular longitudinal profile

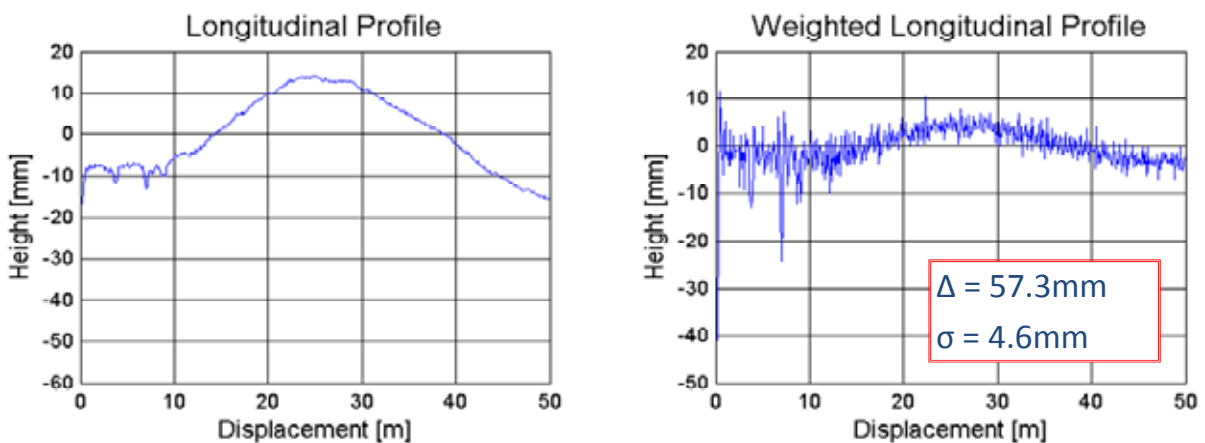


Figure 4 - Evaluation example of transient longitudinal profile

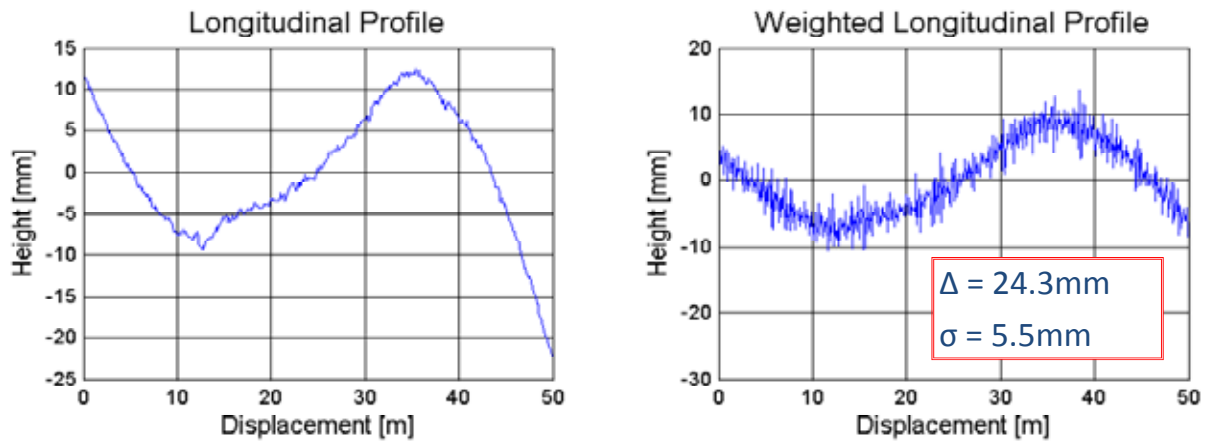


Figure 5 - Evaluation example of wavy longitudinal profile

The result of the evaluation for the respective 50m segments in terms of an evaluation chart is shown (see Fig. 2): the standard deviation (σ) is plotted on the ordinate while the range of WLP (Δ) is plotted on the abscissa. The diagonal marks the relation $\Delta = 6\sigma$. Points that are located near this line denote road segments which exhibit irregular, almost Gaussian unevenness (see Fig. 3). Points in the lower triangle and considerably apart from the diagonal stand for segments with noticeable transient character ($\Delta \gg 6\sigma$), which is the case in Figure 4. Points in the upper triangle and considerably apart from the diagonal represent segments with a “wavy” character ($\Delta \ll 6\sigma$), which is the case in Figure 5. A perfect Gaussian profile would give $\Delta = 6.6\sigma$ and a perfect harmonic profile $\Delta = 2\sqrt{2}\sigma \approx 3\sigma$. The coloured areas in Fig. 2 have the following meanings: blue: better than target value; green: between target and warning value; yellow: between warning and threshold value; red: above threshold value.

So, from the relation between Δ_{WLP} and σ_{WLP} you can get valuable information about the character of the unevenness. This led the people from NEXCO to the idea, whether the relation between Δ_{WLP} and σ_{WLP} could be related to different distress types as well. The results of this investigation are shown in chapter 3.

3. SENSITIVITY ANALYSIS FOR WLP

3.1. Relation to Distress Type

Since specific distress types were unknown there in the SURF 2008 by Maurer et al. [1], sensitivity analysis of the WLP method was further achieved using longitudinal profile data from the Japanese motorways operated by NEXCO. In order to easily assess the sensitivity, the laser-sensor based data were selected from those with the International Roughness Index (IRI) 3.5 or higher. Then the data were classified into several distress groups such as culvert box sites, bridge joint sites, concrete joint sites, cracking sites, and patching sites. Figure 6 depicts the total distress data in the relation between σ_{WLP} and Δ_{WLP} . On the whole there is a tendency of σ_{WLP} going up as with Δ_{WLP} . This tendency was already confirmed in the SURF 2008. However, there could be some more identical tendency for every distress type in Figure 6.

Figure 6 breaks down into Figure 7 with each distress type. Very curiously each distress group shows its own identical tendency between σ_{WLP} and Δ_{WLP} . For example, the culvert box group has a good correlation with wavy pattern, as the slope of regression exceeds $1/6$ which is a boundary deemed as irregular pattern, according to Figure 2. The

bridge joint and concrete joint groups show a correlation with close to irregularity, while the patching has a little tendency with transient pattern, as the slope of regression is steadily going down. In culvert box sites, upper three data at sites #222b, #219a and #221a were from in between two consecutive boxes, while the others from a single box, which thus seems quite reasonable. In bridge joint sites, it is interesting that there is a correlation, regardless of askew angles of the joints. In patching sites, there is a correlation if the origin point (0,0) is not fixed.

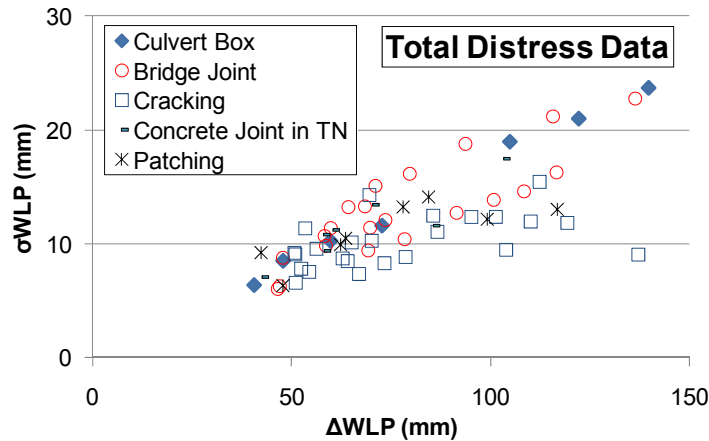


Figure 6 - Relation between σ WLP and Δ WLP for total distress data

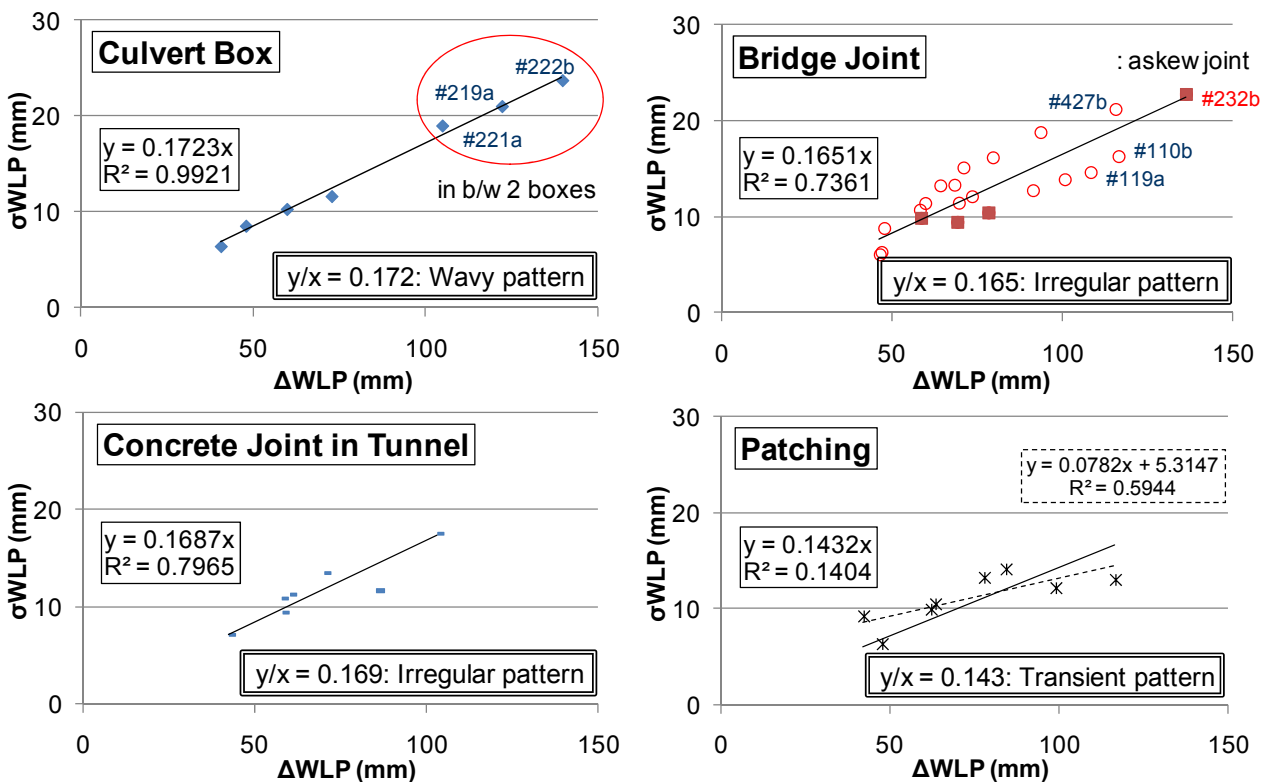


Figure 7 - Relation between σ WLP and Δ WLP for each distress type

In conclusion, all distress data can be well evaluated in a simple relation between σ WLP and Δ WLP, which is very useful for field practitioners to compare.

3.2. Octave Band Analysis

In order to further elucidate the distress pattern, the above original profile data were distributed into nine octave bands. Figure 8 focuses on the relation between Δ and σ of bridge joint sites from octave band #3 with wavelength of 25.6m-12.8m to octave band #6

with that of 3.2m-1.6m. Out of the four figures, octave bands #3 and #4 with 25.6m-6.4m wavelength show higher Δ ranges. This means that these octave bands will share a major part to the original profile. The value of σ tends to dwindle as the octave band number increases, or the wavelength gets shorter. These tendencies were also confirmed in the other three distress types.

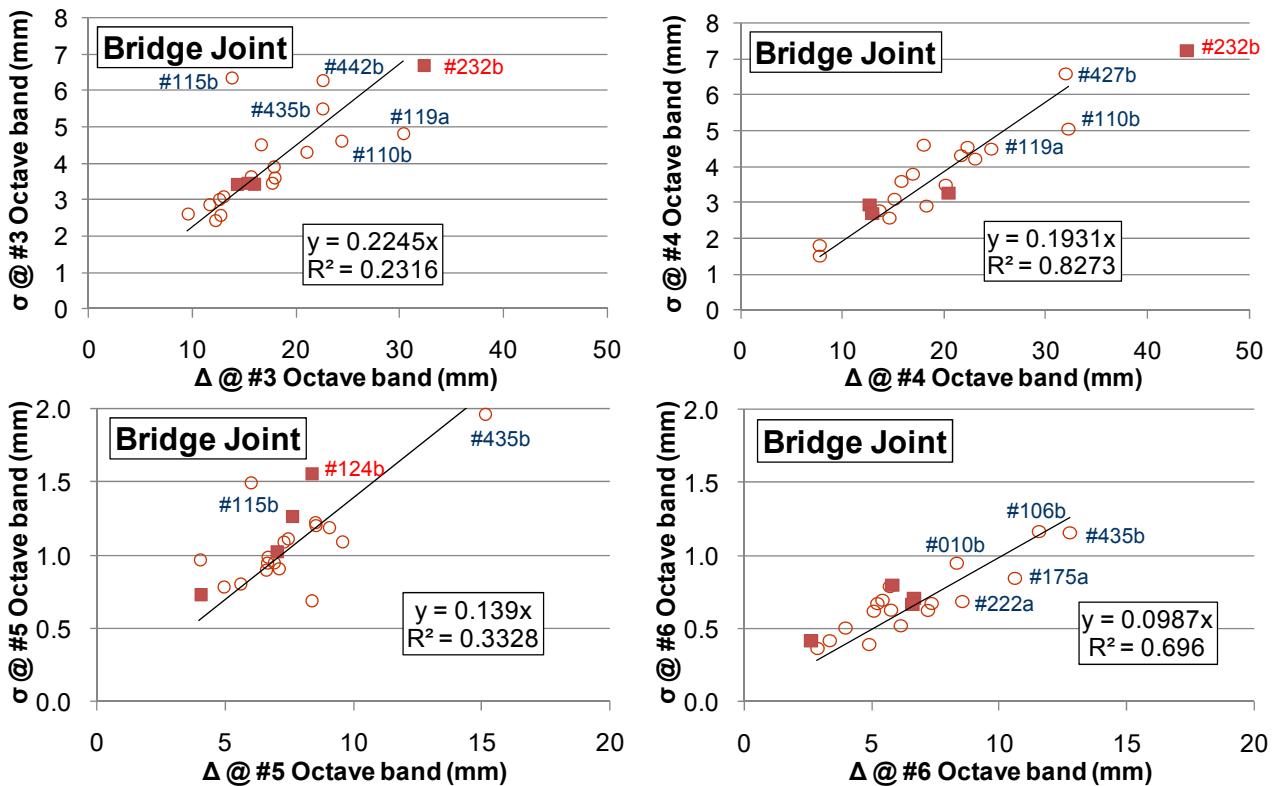


Figure 8 - Relation between σ and Δ of bridge joint sites for each octave band

Data sites with larger Δ WLP such as #232b, #427b, #110b and #119a in the bridge joint part of Figure 7 emerge again upward in octave bands #3 and #4 of Figure 8. Because octave bands #3 and #4 cover all axle distances of commercial vehicles, it can be inferred that changes in surface profile takes place more in these octave bands. Moreover, since octave band #3 includes a higher gain in IRI, the look at this band is quite meaningful for riding quality for road users. Therefore, both octave bands #3 and #4 are considered to give critical values to the original surface profile.

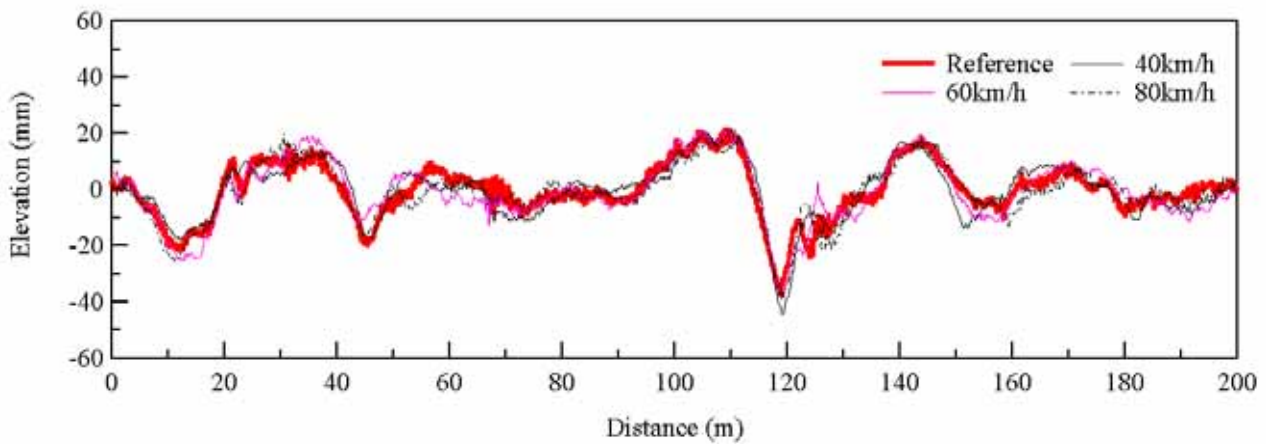
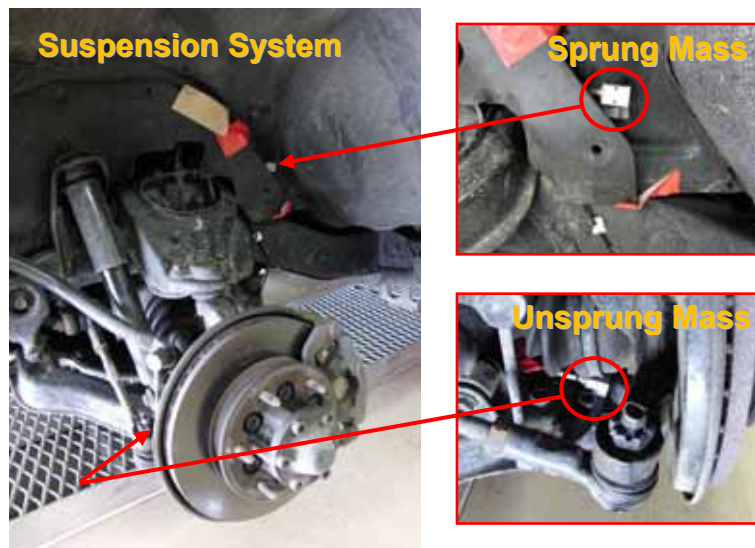
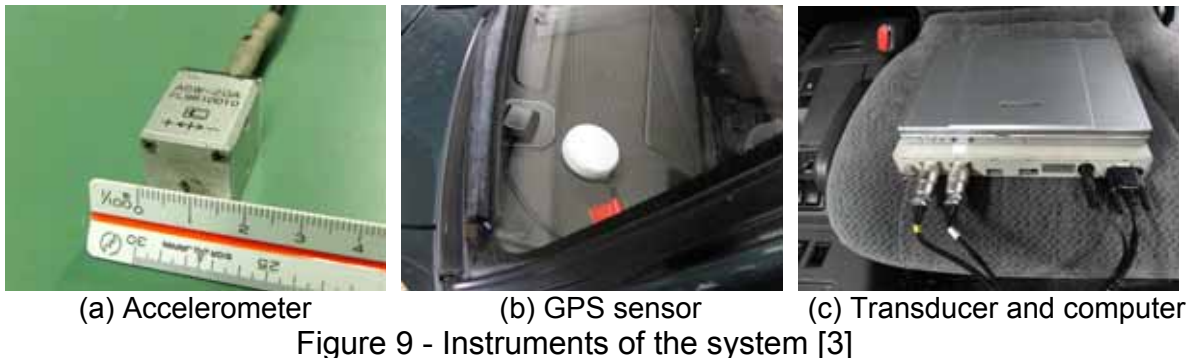
4. A NEW MOBILE PROFILING SYSTEM

4.1. STAMPER

Profile data cannot be collected frequently like every day or week, because a costly road surface vehicle is usually used for the survey. Kitami Institute of Technology developed a methodology to answer to this demand, named STAMPER that is short for a “System with Two Accelerometers for Measuring Profile, Enabling Real-time data collection [2] [3].”

This new system is intended to make profiling cost-effective, time-stable, and easily workable. It consists of two small accelerometers set up on a vehicle suspension system, while conventional high-speed profiling instrumentation uses laser sensors. The back-calculated profile is immediately converted to summary roughness indices such as the International Roughness Index (IRI). The roughness information is then simultaneously

displayed on an onboard computer. Figure 9 and Figure 10 show the system configuration [3].



As designed, STAMPER can calculate a longitudinal elevation profile, based on the back calculation analysis using the two vertical acceleration data. Figure 11 compares the back-calculated profiles for three velocity levels and reference profile, which was manually surveyed by using the rod-and-level and a low-speed profiling device referred as Class 1 [4]. Both data from STAMPER and reference profiling devices were filtered to limit the wavelengths to the range between 0.5 and 50-m which define the wavy characteristics in terms of pavement roughness [5]. As shown in the figure, three profiles measured by

STAMPER closely agree with the reference profile regardless of the traveling speeds. Therefore it is concluded that the back-calculated profile data of STAMPER is reliable in the wavelengths of 0.5 and 50-m.

4.2. Sensitivity Analysis

When certain types of distress are going to show up on the road surface, it is becoming important to look into octave bands #3 and #4 as mentioned in 3.2. In order to investigate the sensitivity of STAMPER data on distress pattern, both STAMPER and LASER based profile data were compared in octave bands #3 and #4. Figure 12 features Δ and σ of bridge joint sites and patching sites, based on wavelet analysis. Each of the two systems clearly shows its own high correlations. More importantly the slope of regression of the two systems is very alike. This means that if there are some different levels of distress, the two systems are distinguishable to the distress in a very similar way. This slope alikeness was also confirmed in the other distress types.

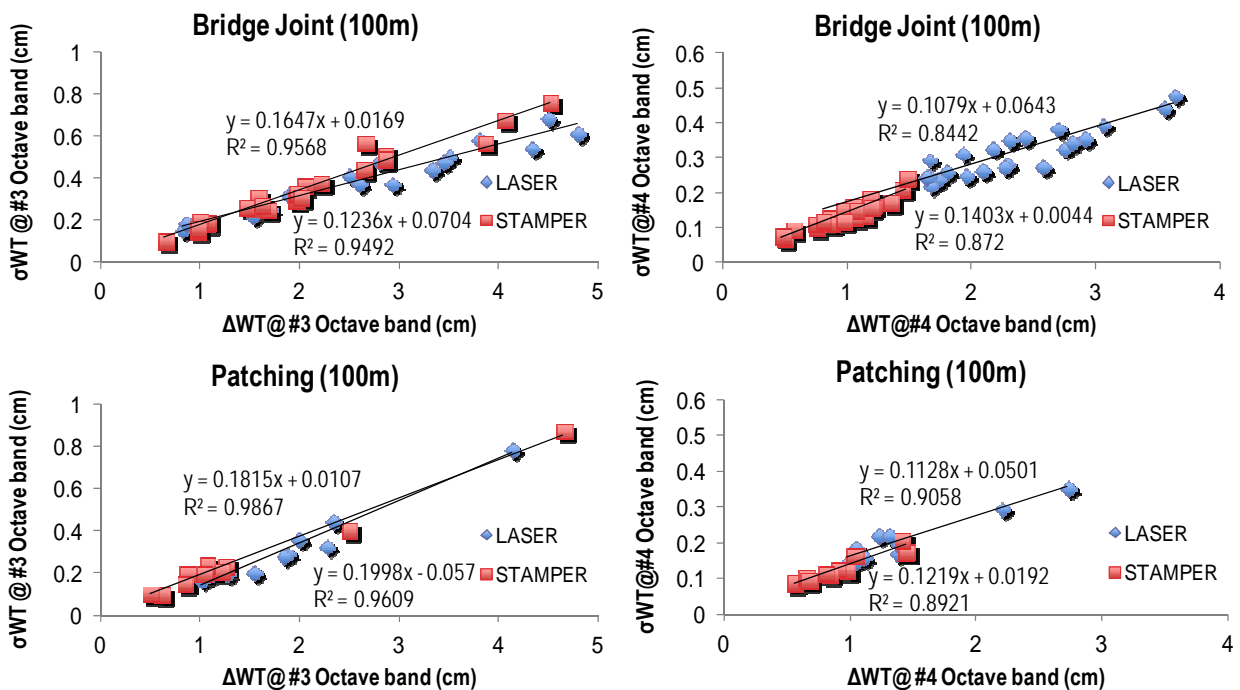


Figure 12 - Comparison of LASER and STAMPER based profile data

5. INNOVATIVE PROFILE COMPARISON

Because STAMPER is a mobile profiling system, you can measure road surface profile anywhere in the world, if only your rent-a-car is equipped with the system. By doing so, it is possible to have any remote data compared very easily as below.

5.1. Autobahn and NEXCO Motorway

Figure 13 plots all the research sections for road roughness in Germany, which were measured on September 22nd through 26th in 2007. The driving route during the five days was an inner circle of Germany, passing through major cities of Strasbourg, Munich, Berlin, Hanover, Cologne and Frankfurt. The length of each section ranges from a few to 30km.

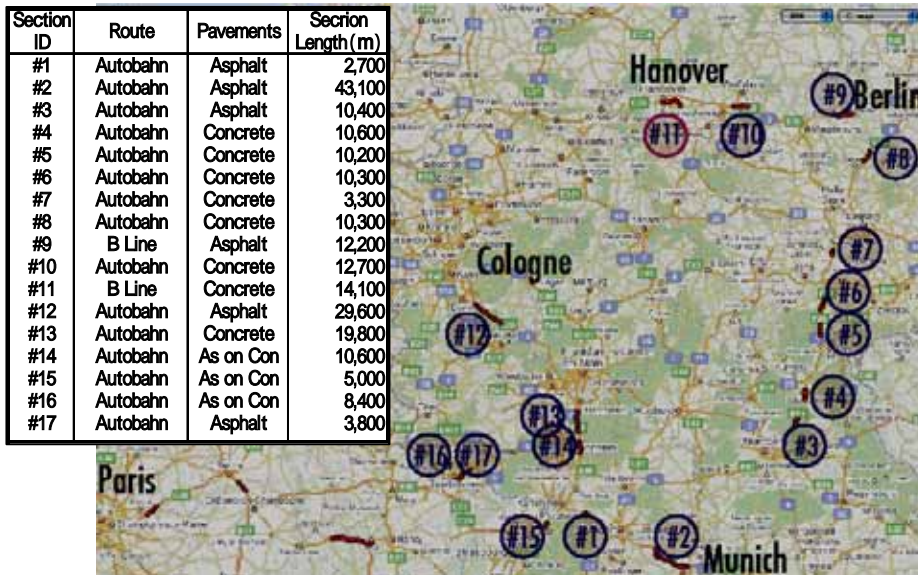


Figure 13 - Research sections

Table 1 - Roughness data unit

	Autobahn	NEXCO	Section Unit
Asphalt Section	448	89,201	200m
Concrete Section	386	6,882	200m
Composite Section	120 (As on Con)	22,468	200m
Total Lengths	190.8km	23,710.2km	

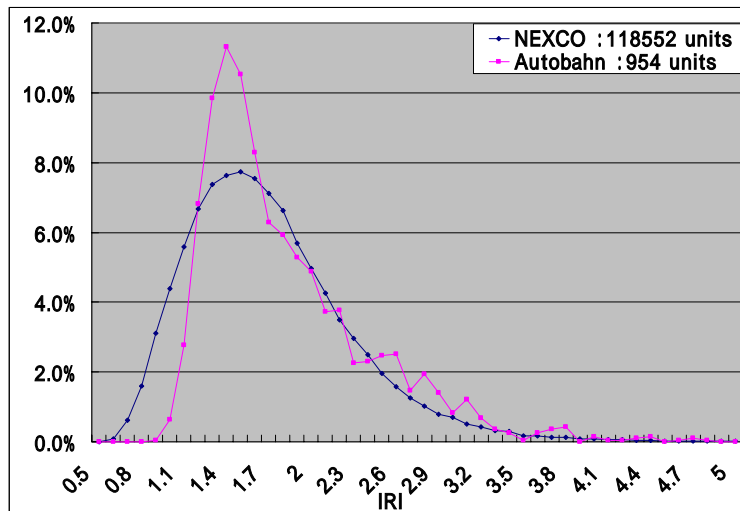


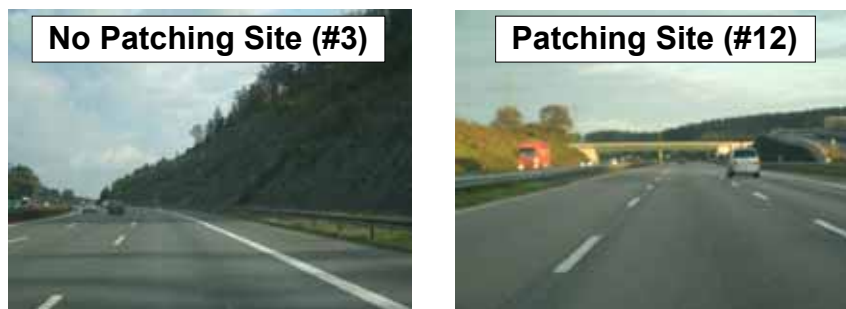
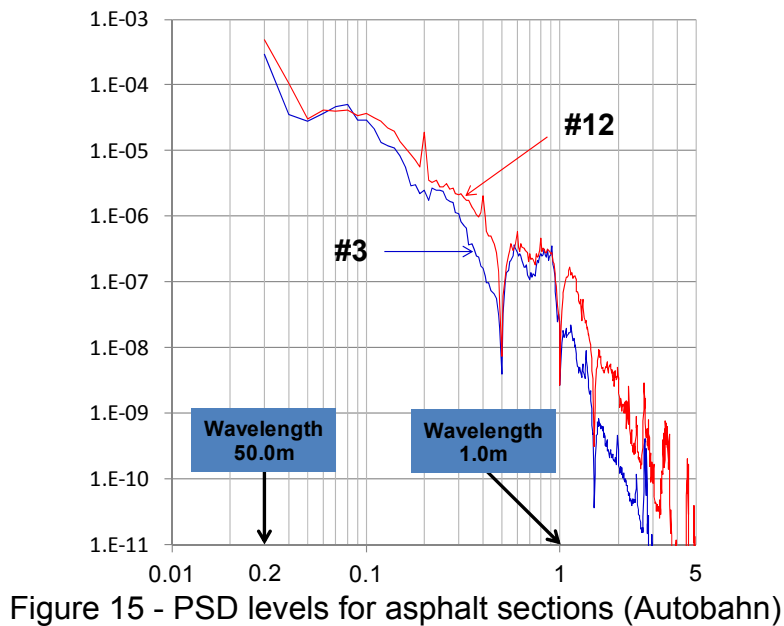
Figure 14 - IRI Comparison between Autobahn & NEXCO motorway

Table 1 sums up the number of roughness data sections of Autobahn and the Japanese motorway, namely NEXCO. A total of 954 Autobahn data consists of 448 two-hundred-meter unit asphalt pavements, 386 unit concrete pavements and 120 unit composite pavements. On the other hand 118,551 NEXCO data consists of 89,201 unit asphalts, 6,882 unit concretes and 22,468 unit composites. Note that Autobahn data was obtained using STAMPER, while NEXCO data using laser profilers. This huge amount of NEXCO data stands for 70% of the total truck lanes nationwide. Although STAMPER data is limited, it covers the truck lanes in heavy traffic sections.

Since STAMPER and laser profiler data are comparable as mentioned in 4.1, Figure 14 is a comparison of IRI between Autobahn and NEXCO motorway. Although data sampling was very limited in Autobahn, IRI is distributed quite similarly between the two motorways.

5.2. Autobahn Sections

Figure 15 compares power spectral density (PSD) functions using the back-calculated data from STAMPER. As mentioned in 4.1, the back-calculated profile data is reliable in the wavelengths of 0.5 and 50-m. The reason why the two sections were selected here is that section #3 showed lower IRI values while #12 showed rather higher IRI value. PSD at #3 is lower than that at #12 in the whole course of wave numbers. Figure 16 represents the differences in road surface condition between the two sections.



In order to compare the relation between σ WLP and Δ WLP for both sections, each 5.0km long section with higher IRI values were selected out of the total 10.4km and 29.6km entities respectively for #3 and #12. Then every 50 data sets of σ WLP and Δ WLP were calculated. Figure 17 compares the relation between both of the 5.0km long sections.

Since the slope of regression at the section #3 exceeds $1/6$, it averagely belongs to wavy pattern. On the other hand, although #12 falls below $1/6$, it must be cautioned whether the section simply falls on transient. This is because all sites other than the circled one at #12 are similarly scattered as #3. More importantly, #3 gives fewer sites with higher σ WLP and Δ WLP values than #12, meaning that road surface at #3 is mostly smoother than at #12.

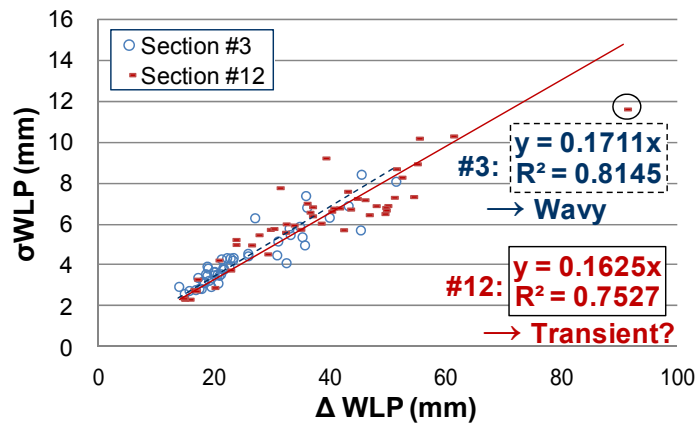


Figure 17 - Relation of σ WLP and Δ WLP (Sections #3 and #12)

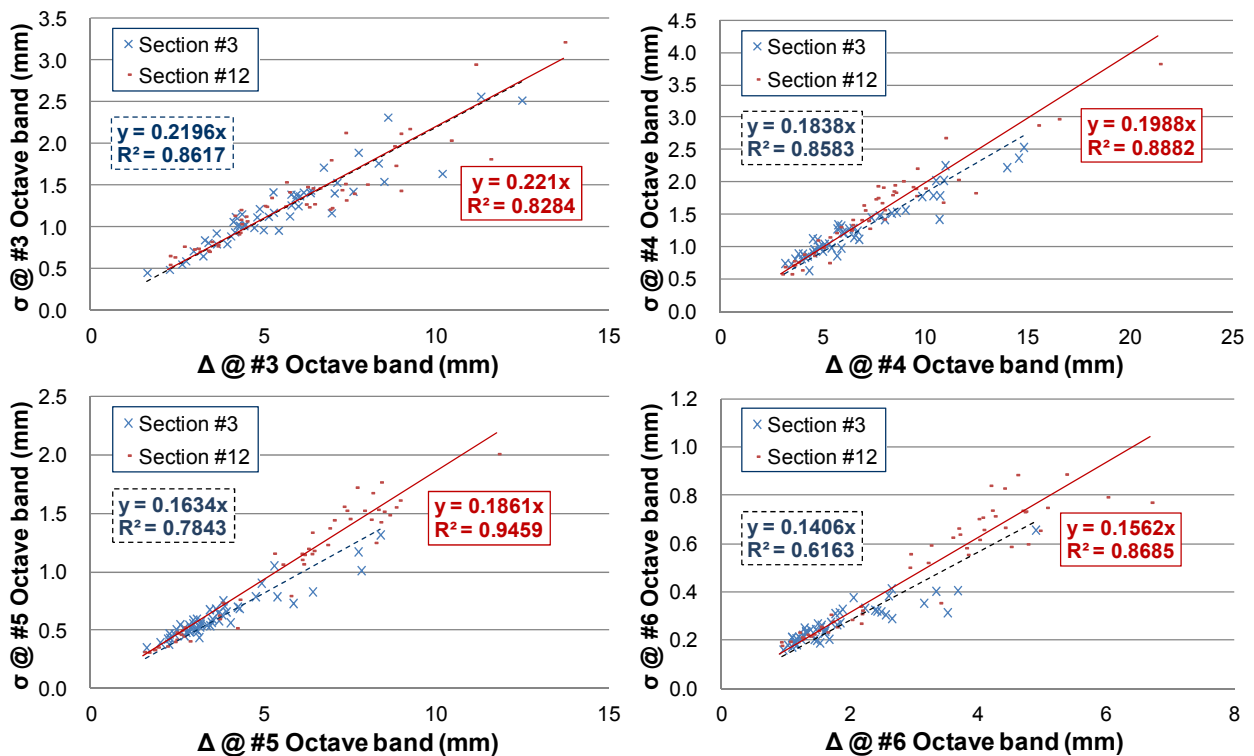


Figure 18 - Relation between σ and Δ of bridge joint sites for each octave band

By focusing on upper data and checking on to the field sites, it is possible to evaluate the severity of distress and prioritize the sites in need for repair activity. This will be a very objective approach of budgeting for road surface distress.

Moreover, major differences between #3 and #12 are to be broken down in Figure 18 with octave bands #3 to #6. Since octave band #6 covers a higher gain in IRI, changes in this band will be crucial to riding quality. The reason why octave bands #3 and #4 as mentioned in 3.2 are not dominant here is considered due to the differences in levels of σ and Δ . The maximum value of Δ in Figure 18 is just over 20mm, while that in Figure 8 exceeds 40mm. Therefore, it is speculated that octave bands #5 and #6 are prevailing when profile variation Δ is low, and that octave bands #3 and #4 are becoming important when Δ gets higher, or road surface gets more deteriorated. This is also true for σ , standard deviation of profile.

6. CONCLUSION

From this study, technical findings are summarized in the following two parts.

Weighted Longitudinal Profile:

According to sensitivity analysis of the WLP method using longitudinal profile data from the Japanese motorways, each distress group showed its own identical tendency in a relationship between Δ WLP and σ WLP. Since data sites with larger Δ WLP of bridge joint show upward in the relation between Δ and σ in octave bands #3 and #4, both octave bands are considered to give critical values to the original surface profile.

It is concluded that road surface distress can be well evaluated in a relation between σ WLP and Δ WLP, thus WLP is a very useful method for field practitioners to compare.

STAMPER:

In comparing STAMPER and laser based profile data in octave bands #3 and #4, the slope of regression between Δ and σ using STAMPER is very close to that using laser profiler. Driving a rent-a-car equipped with STAMPER for just 5 days on Autobahn showed that IRI is distributed quite similarly between Autobahn and NEXCO motorway. By comparing profile data using STAMPER, it was found that octave bands #5 and #6 are prevailing when profile variation Δ is low, or road surface is less deteriorated.

It was proved that STAMPER is a very useful mobile profiling system that enables road surface profile measurement anywhere and comparison of any remote distance.

Because the two methodologies are proved quite useful, if STAMPER can be used for profile measurement in a routine basis and WLP is calculated for every surface distress, road surface control can be upgraded in an innovative and sophisticated way.

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