EVOLUTIONAL PROCESS OF PAVEMENT ROUGHNESS EVALUATION BENEFITING FROM SENSOR TECHNOLOGY

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Abstract - The present paper deals with a view of the availability of high-speed sensor profilers, which has given dramatically increased possibilities to analyze imperfections in pavement surfaces such as roughness. Technical parameters of such profilers, for sensing and analyzing pavement surface profile are described. In addition, the main investigation concentrates on the evolutional process of pavement roughness evaluation. For this purpose a high-speed laser profiler is used to sense roughness data on the surface of a road section that is analyzed both using the International Roughness Index (IRI) and the Power Spectral Density (PSD) approach. Based on the analysis results, some interesting options are shown considering pavement performance in terms of roughness.

Index terms: high-speed sensor profiler, roughness, pavement surface profile, IRI, PSD.

I. INTRODUCTION

Structural capacity seems to be the major concern of many pavement engineers; however road users primarily judge the quality of a road pavement based on its roughness and/or ride quality. Pavement roughness is the principal measure of public satisfaction within a road system. It has been defined as the variation in surface elevation that induces vibrations in traversing vehicles. Earlier studies [1] have shown that rough roads lead to user discomfort, increased travel time due to lower speeds and higher vehicle operating cost. As such, road roughness is now widely recognized as one of the principal measures of pavement performance. Many pavement performance studies have been made based on this measure and with technical advances in automated data collection roughness measurement it has become an affordable and routine practice in many countries [2].

There are various hi-tech systems available for sensing and evaluating pavement roughness. High speed inertial profilers are the most technologically advanced and widely used systems for the estimation of pavement roughness. They record the characteristics of the pavement surface profile at high speeds. For the recording an accelerometer and one or more sensors (lasers), which measure the vertical distance between the accelerometer and the surface, are used. As well, a transducer measures the longitudinal distance traveled by the host vehicle. Measured parameters are post processed to produce the longitudinal surface profile of the surveyed pavement [3].

In order to obtain roughness information from a measured profile, two basic things are required:

(a) The profiler must be capable of sensing the relevant information present in the true profile.

(b) A suitable algorithm must be able to process the measured values to extract the desired information as summary roughness index.

A number of computer-based analysis methods are available to "detect" roughness levels and problem areas in a sensed profile that may affect ride quality and vehicle operation. The application of computerized analysis methods to a surface profile has many advantages - the primary one being, highly repeatable and reproducible roughness results. However, the main problem or obstacle to profile analysis is actually obtaining the profile. The profile survey method used must be quick, economical, detailed and accurate.

Pavement surface profiles comprised of elevation readings can be analyzed for roughness indices such as the IRI (International Roughness Index). Mathematical representations of road profiles can also be used for the study of roughness. These types of analysis require a more thorough knowledge of the distribution of frequencies with accompanying amplitudes. One such approach used for road profiles, is the Power Spectral Density (PSD). The PSD is often approximated with a simple function, using only a few parameters. This PSD approximation can be used both as a concise description of the road roughness level and used either directly in vehicle dynamics or as a basis for road profile generation [4].

The present paper deals with a view of the more or less general availability of high-speed profilers, which has given dramatically increased possibilities to analyze imperfections in pavement surfaces. Technical parameters of such profilers, for sensing and analyzing pavement surface profile are described. Further investigation concentrates on the analysis of roughness data gathered by this profiler for the comparison of the roughness evaluation results based on both the IRI and PSD approach. It seems that although in numerous countries IRI is an acceptable standard for road profile measurements, PSD analysis can provide roughness evaluators with a great deal of information regarding the shape of a pavement surface.

The combination of the above approaches of roughness evaluation can give well-documented information either for the ride perception or for the shape of the pavement surface [5]. However, the simple objective of roughness measurement could be stated as to achieve a single or a number of parameters characterizing the level of roughness of a given section. So far, no such unique index has been developed, due to its intrinsic complication, which, in turn, has made the study of pavement roughness interesting.

II. PAVEMENT ROUGHNESS

a. Basic principles

Roughness is an important criterion for pavement quality control purposes and/or in terms of pavement maintenance strategies because it is the one pavement property most noticeable to the traveling public. As it has been stated above, pavement roughness is the result of surface deviations that produce a response in the suspension system of the vehicles traveling over the road. Since most vehicles travel in well defined wheel paths roughness measurements are typically made in either or both of these wheel paths.

Roughness measurements can be recorded by running a sensor profiler over the test section. In this way the profile elevations can be defined and using standard mathematical techniques such as Fourier analysis, the wavelength of the profile can be determined. This wavelength is the input that the road provides to a vehicle traveling over it. Wavelengths responsible for influencing roughness lie between 0.5 and 50 meters [6].

Vehicles have significant differences in wheel base suspension characteristics as well as different tire and wheel response characteristics. Additionally the way each of these vehicles responds to unit amplitude of road output varies with the frequency of the input.

A roughness index can be derived from the elevation profile, slope profile or even the acceleration profile. When the elevation profile is used as a roughness index, it is found that, if short wavelengths are removed from the profile, there is almost no effect, but if large wavelengths are removed, there is a tremendous decrease in the roughness level. In case of slope profile defined as roughness, there is a reduction in the level of roughness if either large or short wavelengths are removed. For the acceleration profile, on the other hand, if long wavelengths are removed the effect is little, but removal of short wavelengths causes appreciable reduction in the level of roughness.

In any case, the need for a quantifiable measure of pavement roughness is evident.

b. International Roughness Index (IRI)

The World Bank in 1982 sponsored the International Road Roughness Experiment (IRRE). The objective of the experiment was the development of a single calibration and correlation scale for all road roughness measuring systems. The results of IRRE were used for the development of the International Roughness Index (IRI) in 1986 [7].

The International Roughness Index (IRI) is one of the most widely known and used measures as an acceptable standard for road profile measurements [8]. Its calculation is based on the response of a generic automobile to the roughness of the road profile [9]. The reference automobile is a dynamic model, the so-called quarter-car model (Figure 1).

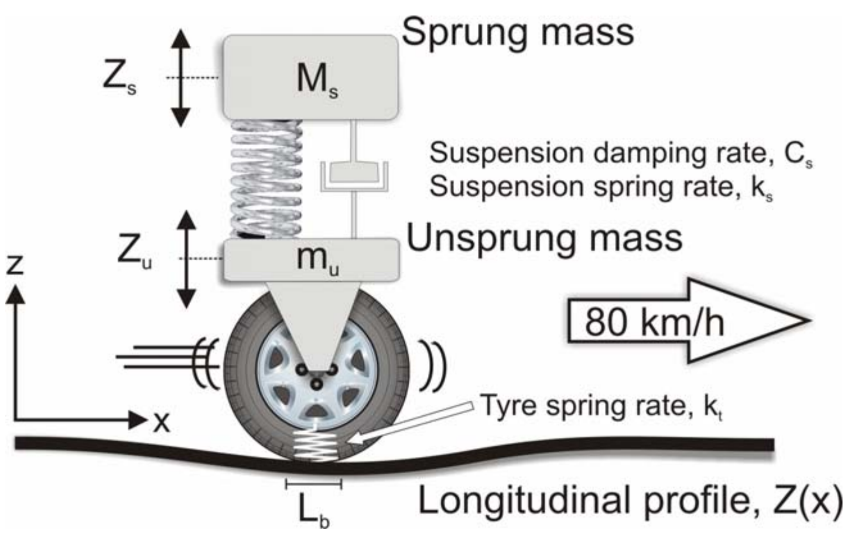

Figure 1. Quarter car model

The quarter-car model is a theoretical model that has standard tire, suspension and damper properties. It is described by the vehicle sprung mass (vehicle body mass) (M_s), the suspension spring (k_s), the suspension damper (C_s), the unsprung mass (m_u) (axle mass) and the tire spring (k_t). The values of these parameters, known as the Golden Car parameters, are given below in Table 1. The model is driven over the measured pavement profile at a constant speed of 80 km/h and the vertical movements of the sprung and unsprung mass are recorded. IRI is the summation of the vertical movements along a base length (mm/m or m/km) [10].

Table 1. Golden car parameters.

Parameter	Value	Unit
k_s/M_s	63.3	s^{-2}
k_t/M_s	653	s^{-2}
C_s/M_s	6	s^{-1}
m_u/M_s	0.15	-

IRI can be expressed as a series of differential equations, which relate to the motions of a simulated quarter-car to the road profile. It is an accumulation of the motion between the sprung and unsprung masses in the quarter-car model, normalized by the length of the profile. Mathematically this can be expressed as follows [9]:

$$\boldsymbol{IRI = \frac{1}{l}\int_0^{l/s} |Z_s - Z_u| dt} \qquad (1)$$

where $\boldsymbol{IRI}$ is expressed in m/km, $\boldsymbol{l}$ is the length of the profile in km, $\boldsymbol{s}$ is the simulated speed (80km/h), $\boldsymbol{Z_s}$ is the time derivative of the height of the sprung mass and $\boldsymbol{Z_u}$ is the time derivative of the height of the unsprung mass.

IRI is used when it is desirable to correlate roughness with general vehicle operating costs, ride quality, dynamic wheel load and with general pavement surface conditions. An IRI value of zero means that the pavement is completely smooth, while a value more than 8 corresponds to a practically impassable pavement, unless a vehicle is moving at very low speeds. Figure 2 shows IRI values for different roads types and different speeds [11].

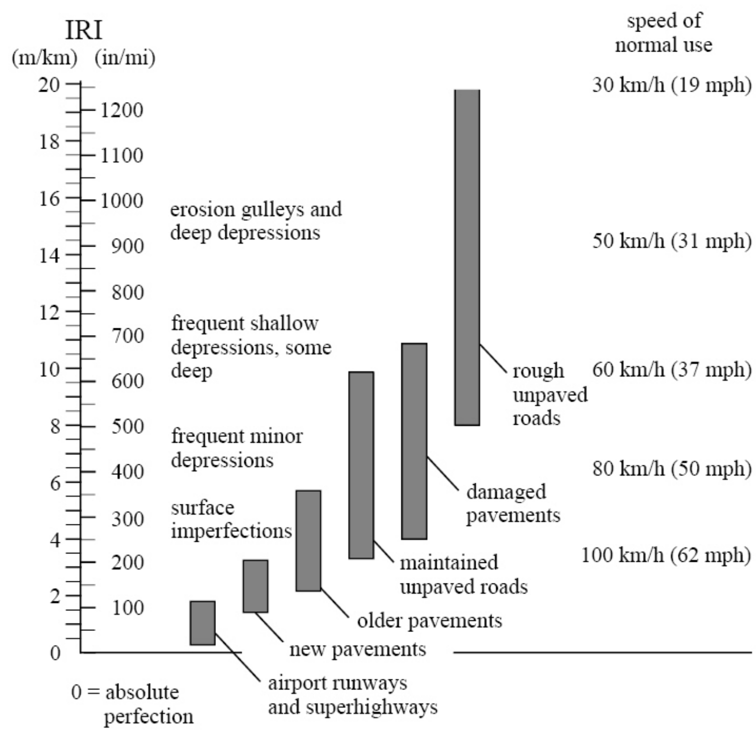

Figure 2. IRI scale

IRI has been developed in order to be linear, portable and stable with time. It is portable since it can be measured with a wide range of equipment giving the same results, and stable with time since it is defined as a mathematical transform of a measured profile, thus it is not affected by the measurement procedure nor the characteristics of the vehicle used for profile measurement. It is based on the concept of a true longitudinal profile, rather than the physical properties of a particular type of instrument.

The measurement and calculation procedure of IRI are based on the following principles [7]:

- A single longitudinal profile with sample interval not longer than 300mm is measured.
- The measured profile is smoothened with a 250mm base length moving average filter.
- The slope between consecutive elevation points is considered to be constant.

The IRI index is calculated by filtering the measured profile with the quarter car filter, at a simulation speed of 80 km/h, so that it provides a summary value of slope, as it is recorded by the theoretical model vehicle. The algorithm used for the IRI value calculation uses a theoretical filter describing the quarter car's theoretical response to pavement surface irregularities.

c. Power Spectral Density (PSD) Analysis

Assuming that the profile of a road is random in nature the Power Spectral Density (PSD) analysis of the surface wavelengths provides a direct statistic of roughness by describing the distribution of the pavement profile variance as a function of wavenumber or wavelength. The height, y, of the surface profile, representing pavement roughness, is a function of spatial distance, x, along the pavement. A couple of Fourier transforms as shown below can be used to compute and reconstruct the profile [12]. When the transform is scaled to show how the variance of the profile is spread out over a set of sinusoids it is known as Power Spectral Density analysis.

$$S_y(\frac{1}{\lambda}) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_y(X) e^{-\frac{i \cdot X}{\lambda}} dX \qquad (2)$$

$$R_y(X) = \int_{-\infty}^{\infty} S_y(X) e^{\frac{i \cdot X}{\lambda}} d(\frac{1}{\lambda}) \qquad (3)$$

Where X represents the distance of two points along the pavement, $S_y(\frac{1}{\lambda})$ is the PSD roughness in terms of wavelength, λ, which represents spatial frequency, and $R_y(X)$ is the spatial auto-correlation function and is defined as:

$$R_y(X) = E[y(x) \cdot y(x+X)] \qquad (4)$$

in which $E[\cdot]$ represents the expectation of a random process that can be estimated from:

$$E[y(x)] = \lim_{X \to \infty} \frac{1}{X}\int_{0}^{X} y(x)dx \qquad (5)$$

From stochastic process theory, PSDs of roughness, $S_y(\omega)$, functions of angular frequency (or cycle frequency) ω, are described by:

$$S_y(\omega) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_y(t) e^{-i \cdot \omega \cdot t} dt \qquad (6)$$

$$R_y(t) = \int_{-\infty}^{\infty} S_y(\omega) e^{i \cdot \omega \cdot t} d\omega \qquad (7)$$

in which t represents time lag, $R_y(t)$ is temporal auto-correlation function.

Furthermore it can be considered that a vehicle moves along a pavement of length X at constant speed v. The relation of length and speed gives that $X = v \cdot t$, where t is the time it takes the vehicle to transverse the pavement section. Substituting this equation into Equation 1, gives:

$$S_y(\frac{1}{\lambda}) = \frac{1}{2\pi}\int_{-\infty}^{\infty} R_y(vt)e^{-i(\frac{\omega}{v})vt}d(vt) = \frac{v}{2\pi}\int_{-\infty}^{\infty} R_y(t)e^{-i\omega t}d(t) = vS_y(\omega) \qquad (8)$$

where $\omega = \frac{v}{\lambda}$.

Another way to define PSD is as the limiting mean-square value of a signal spectrum per unit bandwidth i.e the limit of the mean square value in a rectangular bandwidth, divided by the bandwidth, as the bandwidth approaches zero (CEN 2006). For pavement roughness evaluation, the sinusoids can be plotted either as the PSD of elevation, PSD of slope or even vertical acceleration versus wavenumber (or wavelength). The PSD of slope plots (Figure 3) are commonly used as they offer a more direct view of the slope variance over a pavement providing more detail [13].

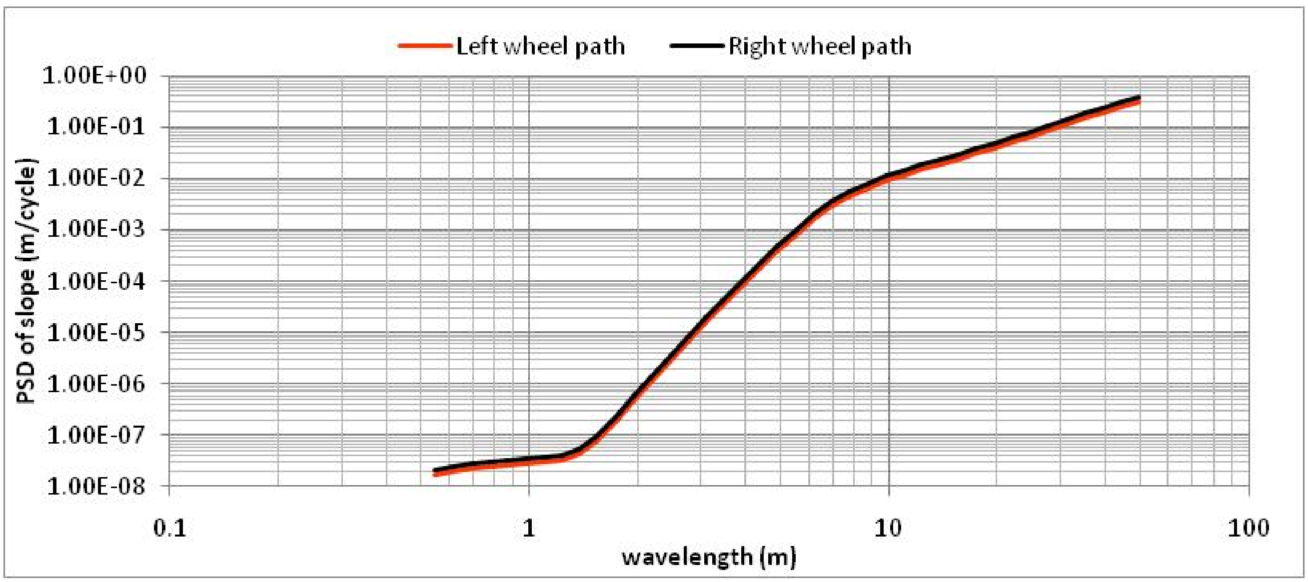

Figure 3. PSD of slope (wavelengths 0.5-50 m)

Moreover slope seems to be a more important parameter of pavement surface properties, than elevation since the latter is of less significance unless the corresponding wavelength is known. These plots can be used for the calculation of an index to evaluate pavement surface conditions. That index is the Root Mean Square (RMS) of elevation or slope calculated from the area below the displacement curve. However the RMS value cannot be considered as a reliable index of pavement smoothness since it is dominated by the longer wavelengths within the band and so it cannot provide an accurate picture of pavement roughness condition. Additionally indices like

RMS do not consider other parameters affecting the perceived roughness like vehicle speed and vehicle characteristics in order to be used to evaluate ride quality.

However, PSD analysis is an important tool for the pavement investigation since it allows the study of pavement's surface characteristics and helps to detect the wavelengths of the pavement's surface profile that are considered responsible for the roughness problem. The knowledge of the existence of certain wavelengths can lead to the appropriate method of maintenance and repair work. Characteristically it is mentioned that short wavelengths (less than 3 m) are a result of irregularities of the top pavement layers while long wavelengths (10 m or longer) are caused by irregularities found in lower pavement layers [14].

III. DESCRIPTION OF A SENSOR PROFILER

A wide range of roughness measuring systems have been developed and utilized over the years. Each of system has its benefits; however the drawbacks of each measuring method are inevitable and may limit their usefulness. Laser profiling systems seem to present several significant advantages that outweigh any disadvantages, especially when sensing the surface profile of a highway pavement. These advantages are listed below [15]:

1. Actual road profiles are a direct output of the device.
2. The operating system is time stable, i.e. the output from the system does not change as the carrier vehicle deteriorates with use.
3. Repeatability from run to run is excellent.
4. Long wavelengths can be detected, measured and analyzed.
5. The operating speed is high enough to be functional for many types of roads and to cover a reasonable mileage of road pavements in a day's time.

Laser profiling systems can also collect other pavement information, in addition to roughness such as pavement texture, cross fall, grade etc. depending on the sensors (lasers) configuration.

The sensor system described is a three Laser Profiler (3LP) which is a vehicle mounted laser based instrumentation equipment [16]. It is capable of sensing the pavement surface profile at vehicle speeds up to 100 km/h recording data in both wheel paths as well as along the center-line of the vehicle. An accelerometer is mounted inside each of the two laser sensor units located in the wheel paths. Their measuring range is set to ±2.5 g.

The laser sensors are attached to the Profiler support frame via a cradle. The frame is bolted to the vehicle tow bar. To ensure correct operation, the support frame must be parallel to the ground when the vehicle is parked on a horizontal surface. Adjustment is available between the shoe and the support frame which allows the laser sensor units to be positioned in such a manner that the laser sensor source is vertical. An eye bubble placed on top of the laser sensor unit aids this adjustment.

The shaft encoder which measures the longitudinal distance traveled by the vehicle is mounted on the rear driver side wheel using a purpose built hub adaptor and modified wheel nuts. A rod fixed to the outer housing of the shaft encoder slides through a guide mounted to the driver side fender that prevents the shaft encoder housing rotating. The guide is positioned so that the line of action of the rod is parallel to the line of action of the wheel relative to the body. In this way, suspensions movements do not cause rotation of the shaft encoder housing which would generate distance pulses unrelated to the forward travel of the vehicle.

The Profiler also contains a signal conditioning rack and a computer system as described in the diagram of Figure 4. In addition the diagram in Figure 5 outlines the connection of the entire system.

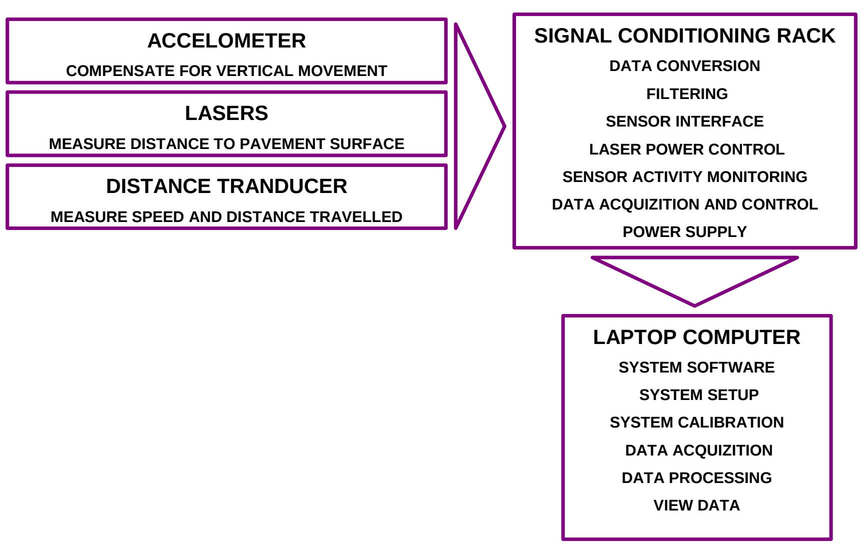

Figure 4. Laser Profiler block diagram

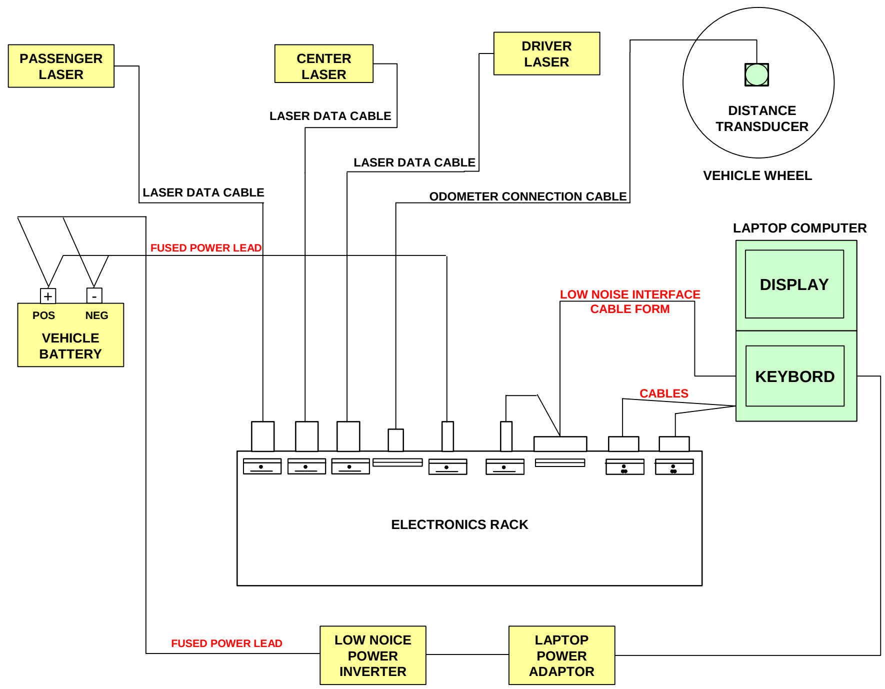

Figure 5. Outline of Laser Profiler System

A similar system owned by the Laboratory of Highway Engineering of the National Technical University of Athens (NTUA) is used for the purpose of the present work (see Figure 6). The performance of this Sensor system is constant and consequently measurements are more reliable. The van hosting the measuring system can move at traffic speeds ranging between 30 and 100 km/h during measurements.

Figure 6. The Laser Profiler of NTUA

Although the Laser Profiler produces enormous volumes of data, data is not information and processing is necessary. Sensed roughness data is stored by the system for further processing and analysis.

III. FIELD DATA ANALYSIS

a. Sensed data

Taking into account the principles of sensor profiler operation a field experiment was undertaken to evaluate pavement roughness. The NTUA Laser Profiler was used for sensing roughness data along an approximately 750 meter trial pavement section of a recently constructed highway. Pavement surface roughness data was sensed in the right lane in both the right and left wheel paths. It is worthwhile to mention that the right lane is the heavy traffic lane; however the experiment is applicable for all traffic lanes.

The field experiment consisted of two phases: 1) roughness measurements recorded shortly after the construction of the new pavement (2005) and 2) roughness measurements recorded two years after the construction (2007).

Taking into account the detailed data sensed by the Profiler, the process of pavement roughness evaluation focused on the comparison of the roughness level detected at the two different testing periods i.e. 2005 and 2007.

b. Processing and analysis

In order to evaluate the pavement roughness, IRI results were calculated from the profile data along each wheel path and reported at 10 m intervals. Figure 7 illustrates the IRI values along the right wheel path in the right lane of the road section for the two testing periods. It seems that although deterioration of the roughness level would be expected after two years of traffic, this is not evident based on the IRI results. In fact no rule seems to be applicable in order to decide if the roughness level is increased or reduced. Pavement surface post-compaction due to 2-years of traffic volume could explain in some cases the reduced IRI values and consequently the improvement of the roughness level. However, more roughness data must be sensed in the future in order to investigate the pavement performance defined by the changes of the pavement surface profile with the passage of time [17].

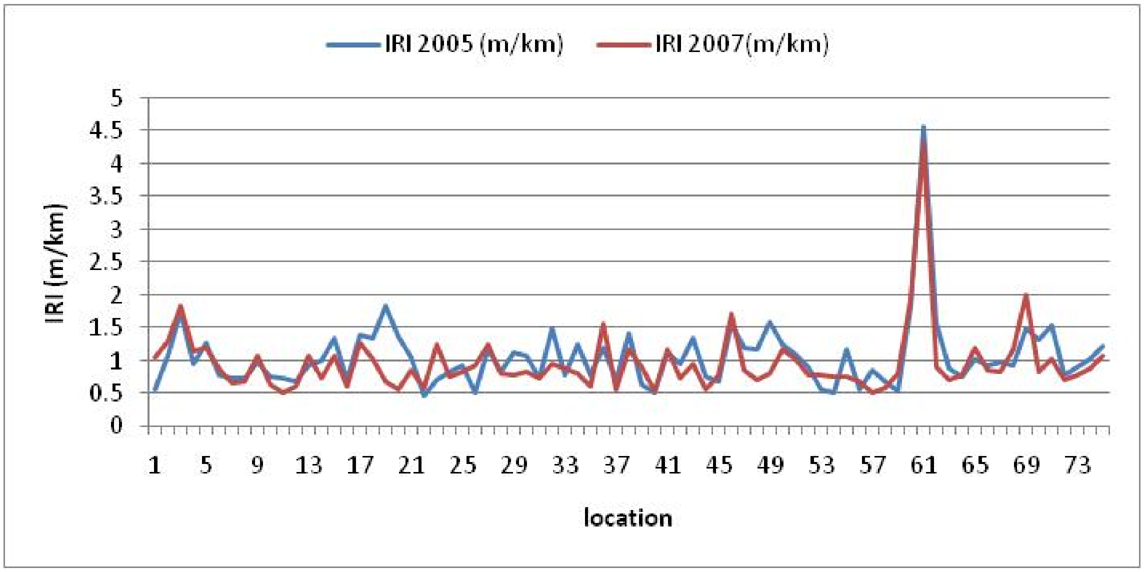

Figure 7. IRI values (right wheel path)

Furthermore if the probability distribution of the absolute differences between the two periods IRI values is examined, gamma distribution can be applied (Figure 8). Specifically it is derived that the random variable x= 'absolute differences between the two periods IRI values' is gamma-distributed. The probability density of the x variable for the gamma distribution presented in Figure 8 is calculated in terms of the gamma function (Γ) as follows:

$$f(x) = \frac{\beta^{-\alpha} x^{\alpha-1} e^{-x/\beta}}{\Gamma(\alpha)} \qquad (9)$$

Where α =1.40 and β =0.17

The goodness-of-fit for the above distribution is based on computing of the Chi-square statistic [18]. This is a quantitative measure of the extent to which the observed counts of values differ from the expected when the null hypothesis H_0: "the data follow the specified distribution" is true.

Due to the gamma distribution the mode value of the variable x (=0.06) could be considered as a representative value of the absolute differences between the two periods IRI values. This value seems to be reasonable according to [19].

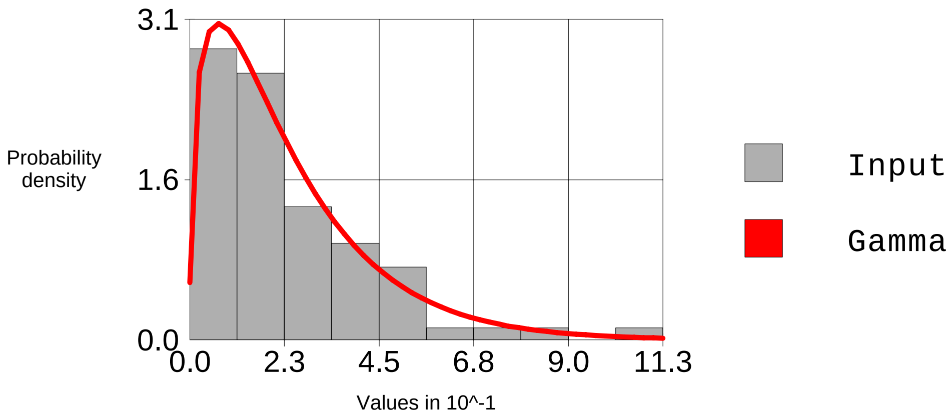

Figure 8. Gamma distribution of the two periods' IRI absolute differences (right wheel path)

In addition to the results above a more profound analysis was applied on the sensed profile data. PSD of slope analysis was performed focusing on the 0.5 – 50 m wavelengths that are responsible for influencing roughness (Figure 9). PSD of slope concerns spectral analysis of slopes in the pavement profile of a road test section. As it has been mentioned the PSD of slope plots are usually more preferable than PSD of elevations or even acceleration as they offer a more direct view of the slope variance over the pavement surface [13]. Moreover, slope seems to be a more important parameter of pavement surface properties, than elevation since the latter is of less significance unless the corresponding wavelength is known.

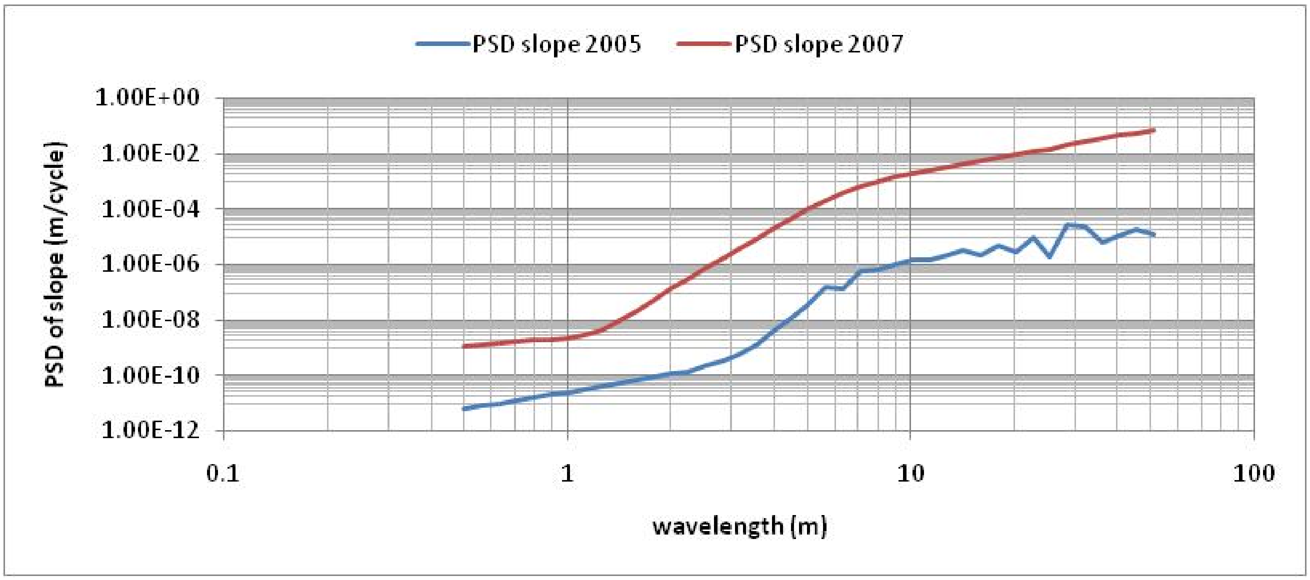

Figure 9. PSD slopes of the two periods' sensed profile (right wheel path)

Figure 9 describes the spectral analysis of slopes in the sensed profile of the test pavement section with respect to the two periods' data. It is shown that after two years of traffic the roughness has deteriorated as the slopes increase for all wavelengths, something that is not evident from the IRI results.

If the probability distribution of differences between the two periods PSD slopes is examined, the Weibull distribution can be applied (Figure 10). The probability density of the variable y= 'differences between the two periods PSD slopes' is calculated as follows:

$$f(y) = \alpha \cdot \beta^{-\alpha} y^{(\alpha-1)} e^{-(\frac{y}{\beta})^{\alpha}} \qquad (10)$$

Where α =0. 19 and β =0.000353

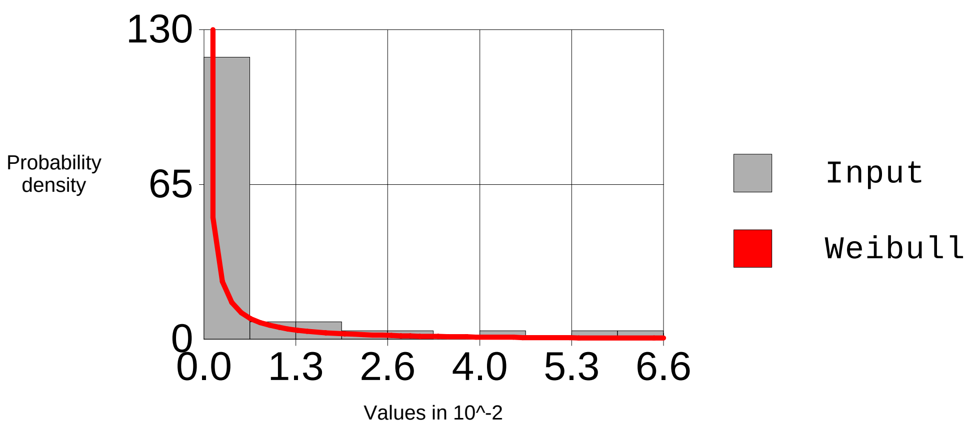

Figure 10. Weibull distribution of the two periods' slope differences (right wheel path)

The goodness-of-fit for the above distribution is based on the computing of the Kolmogorov-Smirnov (K-S) statistic [18]. This is a quantitative measure of the extent to which the observed counts of values differ from the expected when the null hypothesis H_0 is true i.e. "the data follow the specified distribution".

According to the Weibull distribution the mode value of the variable y (=0.003295) could be considered as a representative value of the differences between the two periods slope values. This value is not high but nor marginal either considering that the pavement surface profile is sensed and examined in terms of a short period of time (two years).

The results above are based on the analysis of the profile sensed along the right wheel path in the right lane of the road test section. Similar results arise when the pavement surface profile along the left wheel path is analyzed.

CONCLUSIONS

Advances in sensor technology and data acquisition systems have led to the development of so-called laser profilers that can measure road surface profiles at relatively high speeds and consequently at reasonable cost. These sensors collect vast amounts of data that need to be processed and reduced to provide useful information.

The simplest option is to use the sensed profile data to calculate the IRI values for the profiles. This is a widely accepted and understood roughness measure. IRI is useful as it summarizes the roughness qualities that impact vehicle response and is considered appropriate where a roughness measure that relates the overall ride quality to the pavement surface condition is required. However an IRI value cannot express pavement surface profile properties that induce the surface irregularities.

It is possible to analyze the surface profile's irregularities to different sinusoids by using the Fourier transforms. Based on the PSD approach, the Fourier transforms lead to the calculation of the variance of the profile that is distributed over a set of sinusoids. PSD analysis is more sophisticated than IRI because they distinguish which wavelengths are contributing to the roughness. However in order to obtain a good estimate of the PSD, it is necessary to have a long sample; this is easily created by sensing the pavement surface profile with a laser profiler.

In terms of the present work roughness data was sensed shortly after the construction of a new pavement and two years after construction. Analysis results focused on the comparison of the pavement surface profile sensed for the two time periods. The evolutional process of the pavement roughness evaluation based on IRI approach and PSD analysis provided valuable information about the progress of the roughness with the passage of time.

So although a criteria-cued value of the absolute differences of the two periods IRIs is assigned, there is no rule applied to describe the phenomenon of the IRIs change. More roughness data needs to be sensed in order to describe the change of the roughness level with the passage of time.

As far as the PSD analysis results are concerned the sensed profile was classified in bands of wavelengths. Based on the two periods' sensed data analysis, the developed PSD plot provided a comparative view of the slope variance over the pavement surface. It was shown that after two years of traffic the roughness deteriorated as the slopes increased for all wavelengths, something not evident from the IRI results.

Although the slope value increases were not high, the need to sense and monitor periodically the pavement roughness is more than evident in order to preserve the ride quality of the road. More roughness monitoring is required when a pavement management system (PMS) is applied. The capability of high-speed sensor profilers to collect a vast amount of roughness data facilitates pavement roughness monitoring and enables the operational functions of a PMS system.

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