Characterization of pavement surface undulations using side view images

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Abstract. Pavement surface undulations affect friction, ride comfort, water drainage, noise etc. Various indices have been proposed in the literature to characterize the pavement surface undulations. The present paper compares a few pavement surface undulation indices in the spatial domain and the frequency domain. For this study, core samples of pavement surface were collected from freshly constructed pavements, which had not been opened to the traffic yet. The core samples were sliced using a high-speed diamond saw. Images of the side view of the slices were captured using a digital camera. Suitable image processing scheme was employed to detect the pavement surface profiles. Various indices were subsequently estimated and compared.

1. Introduction
Pavement surface undulations affect various engineering properties, arising from tyre-pavement interaction, namely friction [1], ride comfort [2], water drainage [3], noise [4], etc. [5]. Some of the traditional methods of measuring the pavement surface undulations are sand patch test [6], outflow meter test [7], etc. and some of the emerging methods of measuring the pavement surface undulations are laser-based triangulation [8,9], close-range photogrammetry [10,11] etc.

Various spatial domain based indices have been proposed in the mechanical engineering literature (for example, the Average Maximum Profile Peak Height, Maximum Profile Peak Height, Maximum Profile Valley Depth, Mean Width of Profile Elements, Arithmetic Average Height and so on [12,13]) and in the pavement engineering literature (for example, the Mean Profile Depth (MPD) [14,15]). Various frequency domain based indices have been used in the mechanical engineering literature (for example, the power spectral density (PSD) [16]) and moment of PSD [17]) and in the pavement engineering literature (for example, the PSD [18,19]). In this study, a few spatial domain and frequency domain based indices are estimated (for various pavement surface profiles) and compared. The indices compared in this study are the Average Maximum Profile Peak Height ($R_{pm}$) [13], Arithmetic Average Height ($R_a$) [13] and the power of the surface undulations ($P$) in two different frequency bands ($P_1$ and $P_2$)[20].

2. Background
In this section, a brief discussion on the indices used in this study ($R_{pm}$, $R_a$ and $P$) is presented.

2.1. Average Maximum Profile Peak Height
Let a point measured in the profile have its height $Y_i$ and be located at a distance $X_i$, as illustrated in figure 1. The level of the ‘mean height’, as shown in figure 1, is the average of the measured height of all the points in the profile. Let this profile of arbitrary length ‘L’ be divided into ‘n’ segments of equal
lengths ‘\(L/n\)’. Let, the maximum height of the profile in \(i^{th}\) segment be \(R_{pi}\), for example, the maximum height of the first segment is \(R_{p1}\), as illustrated in figure 1.

![Figure 1. Schematic diagram explaining the concept of the Average Maximum Profile Peak Height.](image)

Then, the Arithmetic Maximum Profile Peak Height \((R_{pm})\) is given by equation (1)[13]:

\[
R_{pm} = \frac{\sum_{i=1}^{n} R_{pi}}{n}
\]  (1)

2.2. Arithmetic Average Height
The Arithmetic Average Height \((R_a)\) is the sum of the absolute value of the heights of each point in the profile, divided by the length of the profile [13]. Let the number of such points measured in that profile shown in figure 1 be \(N\), then the \(R_a\) is given by equation (2)[13]:

\[
R_a = \frac{\sum_{i=1}^{N} |Y_i|}{N}
\]  (2)

2.3. Power of the surface undulations
Power of a signal, in electrical engineering terminology, is defined as the sum of the squares of the amplitude of the sinusoids (obtained by Fourier Transform of the signal) divided by \(N^2\) [20]. Assuming the sampling frequency of the signal as \(F_s\), the frequency and the amplitude of the \(i^{th}\) sinusoid as \(f_i\) and \(A_i\) respectively, then the power of the surface undulations is given by equation (3) [20]:

\[
P = \frac{2}{N^2} \sum_{i=1}^{N} |A_i|^2
\]  (3)

where, \(f_i = i \times F_s/N\). In the present work, the frequency band is divided into two parts: any frequency ranging between 0.1 cycles/mm to 8 cycles/mm and any frequency ranging between 8 cycles/mm to 20 cycles/mm. Thus the indices \(P_1\) and \(P_2\) are expressed as given in equation (4) and equation (5):

\[
P_1 = \frac{2}{N^2} \sum_{i=1}^{N} |A_i|^2 \text{ for } 0.1 \leq f_i \leq 8
\]  (4)

\[
P_2 = \frac{2}{N^2} \sum_{i=1}^{N} |A_i|^2 \text{ for } 8 \leq f_i \leq 20
\]  (5)

3. Experimental studies
In the present study, one hundred twenty-five (125) pavement slices were obtained from 17 pavement cores acquired from different parts of India. These cores were extracted from freshly constructed...
pavements on which no vehicle had passed, as the purpose of the study was to characterise pavement surface which had not undergone polishing and/or wearing due to the passage of tyres on them. The gradation of all the core samples were Bituminous Concrete Grading 2, specified in MoRT&H guidelines, Government of India [21]. The following sections describe the sample preparation, the image acquisition and subsequently, the profile detection and the estimation of the indices.

3.1. Sample preparation
Various stages of sample preparation are shown in figure 2. Figure 2(a) shows a representative pavement core sample. To protect aggregates on top of the core from being dislodged during the cutting process, the pavement core surfaces were covered with an epoxy resin mixture. Pavement core samples were cut using a high-speed diamond saw to obtain slices (figure 2(b)).

![Figure 2(a). The original pavement core sample.](image)

![Figure 2(b). The pavement slice was cut from the core.](image)

3.2. Image acquisition
Images of the side view of these slices were captured (see figure 3) using a digital camera (aperture f/6.3, shutter speed 1/60th of a second and focal length 24mm). A graph paper (with a known dimension of the grid boxes) was placed on the top of the slices for calibration. A white sheet was kept as background (with pixel values close to 255), and care was taken so that the presence of dirt on the white paper (with pixel values close to 0) did not interfere with the profile detection scheme employed subsequently.

3.3. Profile detection and estimation of indices
The following steps were taken to detect the profile:
Thresholding [22] was applied to the images acquired. The thresholding operation converted all the pixels covered by pavement core into black (pixel value 0) and all the pixels covered by the resin and the white paper background into white (pixel value 255) making it a binary image. Figure 4 shows a representative binary image of the pavement slice after thresholding.

Figure 3. A typical image acquired of the pavement slice.

Figure 4. A typical image after thresholding.

It was envisaged that by enhancing the contrast between the pavement core and the resin layer, thresholding would work more efficiently and surface profile detection will be unambiguous. Thus, a backlit light source was placed, which illuminated the resin layer and the pavement core. A schematic diagram of the setup is shown in figure 5. With this illumination, the image of the pavement core became darker than it originally was, and the image of resin layer become lighter than it originally was. Hence, the boundary demarcation between the resin layer and the pavement core became sharper than the former boundary.

The change of the pixel value from 255 (white) to 0 (black) was treated as the boundary (see figure 6). This boundary indicates the pavement profile.

The actual dimension of the graph paper grid was used for scaling the profiles to their actual lengths (individually for all the 125 slices). The length of each slice was kept uniform (75 mm) for further analysis.

Subsequently, the indices \( R_{pm}, R_a, P_1 \) and \( P_2 \) of the 125 profiles were obtained. The definition of these indices has already been discussed in Section 2, titled ‘Background’. For calculation of \( R_{pm} \) the profile was divided into five equal halves of 15 mm each. For the calculation of \( P_1 \) and \( P_2 \), Discrete Fourier Transform was performed on MATLAB® [23].
Figure 5. A setup shown for enhancement of contrast between the resin and the pavement core.

Figure 6. A typical pavement surface profile obtained after image processing.

4. Results
The $R_{pm}$, $R_a$, $P_1$ and $P_2$ values are plotted in figures 7-10. As seen in figures 7-10, across the various profiles, the $R_{pm}$ and $R_a$ follow a similar pattern, while $P_1$ and $P_2$ do not follow the pattern of $R_{pm}$ and $R_a$. The possible reason is explained in the following:

- The actual dimension of the graph paper grid was used for scaling the profiles to their actual lengths (individually for all the 125 slices). The length of each slice was kept uniform (75 mm) for further analysis. Thus, it may be possible that two different pavement surface profiles, having disparate amplitude-frequency distribution of the sinusoidal waves, can have comparable values for the peak heights present in both profiles. Thus, the $R_{pm}$ values may turn out to be same, although the two profiles may be characteristically different.
- Similar reasons can be said for $R_a$. 

5
Figure 7. $R_{pm}$ obtained for the various pavement surface profiles.

Figure 8. $R_{a}$ obtained for the various pavement surface profiles.

Figure 9. $P_{1}$ obtained for the various pavement surface profiles.
5. Discussions
In this study, two spatial domain and two frequency domain based indices have been compared for characterizing pavement surface undulations. The indices compared are the $R_{pm}$, $R_a$ and the power of the surface undulations in two different frequency bands. It is observed that $R_{pm}$ and $R_a$ vary in a similar pattern, while $P_1$ and $P_2$ do not follow their pattern.

In the present method, illumination scheme discussed in Section 3.3 had been adopted. This helped in enhancing the contrast. However, since backlit light-source was used, the surface undulations detected were the highest of elevation value of all possible elevation values of the points from one edge (A-B) of the slice to the other (C-D), as schematically explained through figure 11. Making the slices thinner would reduce this problem. Thus, efforts were made to reduce the thickness of the slices as far as practicable.

Figure 10. $P_2$ obtained for the various pavement surface profiles.

Figure 11. Schematic diagram of the sliced portion.

Acknowledgements
The authors sincerely thank Dr. K S Venkatesh, Professor, Department of Electrical Engineering, IIT Kanpur for the useful discussions. The authors also thank Mr. Shailendra Kumar Tiwary from Oriental Structural Engineers Pvt. Ltd., Mr. Bidur Jha and Mr. Shahu J Patil from LEA Associates South Asia Pvt. Ltd., Mr. Anuj Narula from M/s Teckkonnect, Mr. Sunil Yadav from H.G. Infra Engineering Limited, and Ms. Atasi Das from G R Infraprojects Limited for providing the pavement cores used in this study. The authors wish to thank Mr. Rahul Kumar, Experimental Rock Deformation Laboratory, Department of Earth Sciences, IIT Kanpur for his help in cutting the pavement cores.
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