

APPARE: Personal Computer Software for Automated Pavement Profile Analysis and Roughness Evaluation

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Profilographs are widely used for characterization, specification, and quality control of initial pavement roughness during highway construction. Pavement roughness is indicated by a profile index (PI). The PI is usually evaluated manually from the profilogram, which is a strip chart of profile traces, using a blanking band profile index (BBPI) algorithm. The manual BBPI algorithm is laborious, subjective, and prone to operator errors; thus results are highly unreliable and unrepeatable. A new personal computer software package, APPARE (automated pavement profile analysis and roughness evaluation), currently being developed at the Louisiana State University using the profilogram and other types of digitized pavement profile data, is reported. APPARE has an interactive graphical user interface and an image-processing engine capable of digitizing profilograms using commercially available, low-cost desktop scanners; it evaluates the PI and other widely used roughness indexes, such as international roughness index, using digitized pavement profile data from any profiling and roughness measuring instrument. In particular, a fine-tuned computer BBPI algorithm is developed and successfully implemented.

A smooth road not only provides a comfortable ride for its users but also reduces vehicle wear and tear, improves fuel efficiency and safety of travel, and prolongs the life span of the pavement. Two main aspects of pavement smoothness that concern highway engineers and management authorities are (a) smoothness of newly constructed pavements and (b) performance of the entire highway system (1). Controlling the initial roughness during construction can significantly improve the life cycle of the road, consequently greatly reducing the cost of maintenance (1). The 1986 AASHTO *Guide for Design of Pavement Structures* emphasizes the need for initial pavement smoothness as an important design consideration (2).

Profilographs are widely used instruments for characterization, specification, and quality control of initial pavement roughness during highway construction. Commonly used profilographs (e.g., the Rainhart and California type) generate strip charts called profilograms. Pavement roughness is usually evaluated manually from the profilograms using a blanking band profile index (BBPI) algorithm to derive a profile index (PI) (3). This process is known as trace reduction. Consensus appears to be that the manual BBPI algorithm is laborious, subjective, and prone to operator errors (1,4-6). Consequently, the results are highly unreliable and unrepeatable. For instance, it has been reported that manual calculation of the PI using the BBPI could vary as much as 65

m/km (4 in./mi) from one operator to another (4-7). In particular, it was found previously (7) that the PI of a sample of 19 profilograms evaluated by 23 different operators, 8 were considered experienced operators, and 2 computer algorithms had an average standard deviation some 52 percent of the mean PI; that is, there is a 32 percent chance that an average operator/computer will produce a PI that deviates from the "true" PI by more than ± 50 percent.

To improve objectivity and repeatability, attempts have been made to computerize the profilograph data acquisition and trace reduction process (4-8). However, those previous attempts reportedly have been prone to either under- or over-estimating the PI (5-8). In one study the problem was attributed to the difficulty in selecting an appropriate (linear) filtering algorithm in profile trace reduction (8).

In addition to the difficulties in PI evaluation, it is well known that the profilographs severely distort the "frequency components" in the pavement profile (4,9-12), and the PI correlates poorly with other widely used roughness indexes, such as the international roughness index (IRI) (4,10,13). Consequently, TRB has recommended further study and evaluation of the profile trace (profilogram) produced by the profilograph (1).

The present paper together with two other accompanying papers (14,15) constitute an ongoing research effort on further study of profilographs sponsored by the Louisiana Department of Transportation and Development/Louisiana Transportation Research Center (LDOTD/LTRC), in cooperation with FHWA, U.S. Department of Transportation. The problem of and remedies for poor correlation of the PI with IRI and other widely used roughness indexes are addressed in the accompanying papers, so in this paper a new personal computer software package, APPARE (for automated pavement profile analysis and roughness evaluation), currently being developed at the Louisiana State University, is discussed.

APPARE has an interactive graphical user interface and an image-processing engine capable of digitizing profilograms using commercially available, low-cost desktop scanners, displaying, editing, and vectorizing raster images and evaluating various roughness indexes using digitized pavement profile data from a profilograph and other profiling instruments. Corrective filtering algorithms are implemented for statistically recovering the pavement profile from distorted profilogram data or data of other profiling devices to ensure the validity and repeatability of the PI. A fine-tuned computer BBPI algorithm was developed and successfully implemented. On test data from 27 road sections, a highly linear correlation

was obtained with an R^2 of 0.991 between the PIs evaluated by APPARE and by manual evaluation with strictly controlled precision. In addition, the evaluation of IRI and other widely used roughness indexes are facilitated for easy correlation analysis of the pavement roughness. Future development of this software includes the following: capabilities for power spectral analysis of pavement profiles, quarter-car simulation, and other tools for pavement surface and rideability analysis.

DEVELOPMENT AND FUNCTIONALITY OF APPARE

APPARE is a self-contained computer program developed to analyze pavement roughness from road elevation profiles. It contains three functional modules, as shown in Figure 1, to automate the process of (a) digitizing profile measurements if necessary, (b) statistically compensating for pavement profile distortions caused by profile measuring equipment, and (c) calculating and mathematically correlating (converting) the various commonly used roughness indexes. These functionalities are discussed in detail in the following subsections.

Profilogram Digitizer

Because of some reported instances of unsuccessful implementation of computerized profilographs (5,6,8), profilographs using strip chart recorders are still widely in use in many states, including Louisiana. To automate the profile trace reduction procedure, the first step is to convert the graphical profilogram (a strip chart) into a numerical format for computer processing. In APPARE this digitizing process is achieved through a three-step procedure: (a) scanning the profilogram, (b) editing the scanned image if necessary, and (c) extracting the digitized profile trace from the scanned image. Salient features of this procedure include the use of

commercially available, inexpensive desktop scanners, an interactive graphical editor, and a nonlinear midpoint profile extraction filter with a moving slope threshold for noise reduction.

Scanning Profilogram

A profilogram is usually a multipage fan-fold continuous form [216 × 280 mm (8.5 × 11 in.)]. For California-type profilograph using a 1:1 vertical scale and a 1:300 (1 in. to 25 ft) longitudinal scale, a 0.322-km (0.2-mi) profilogram consists of at least 4, sometimes 5, pages. These pages can be scanned using a desktop digital scanner either continuously through one pass or page by page. The scanned image is called a raster image, which consists of an array of white and black dots known as pixels. At 12 dots/mm (300 dots/in.) scanning resolution and using the above profilogram scaling ratio, the scanned profile trace has a vertical resolution of 1/12 mm (1/300 in.) and a longitudinal resolution of 25.4 mm (1 in.). The scanned raster image can then be stored on a computer disk in some standard raster graphical image file format such as PCX format, TIFF format, and so on. The scanning and processing routines in APPARE can handle both single-page continuous-form and multipage scanning and can support the PCX format now and the TIFF format in the near future.

Shown in Figure 2 is a screen snapshot of the scanned profile trace displayed by the Microsoft (MS) DOS version of APPARE. Figure 3 shows the screen display of the MS Windows version of APPARE.

Graphical Editor

Although the scanned images are usually of very high quality, at times they need some touch-up to remove spurious dots and streaks that do not belong to the profile trace. Moreover, sometimes it is difficult for the computer to determine where the profile trace actually starts and ends, and sometimes it may be desirable to select a section of the scanned profile trace to process; in such cases, manually selecting the start

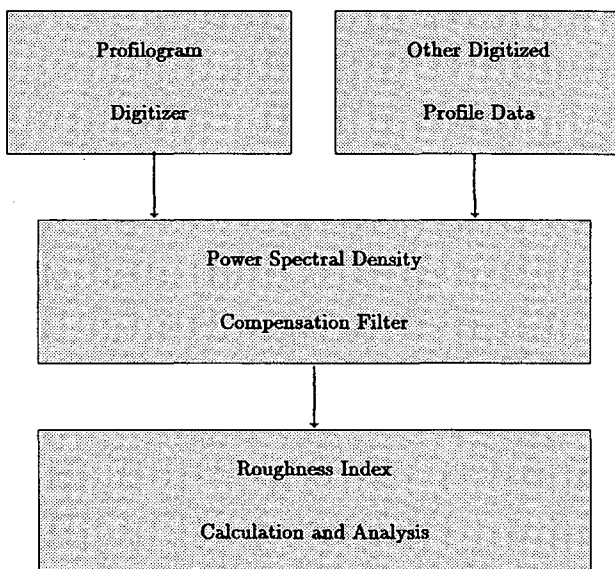


FIGURE 1 Functional flow chart of APPARE.

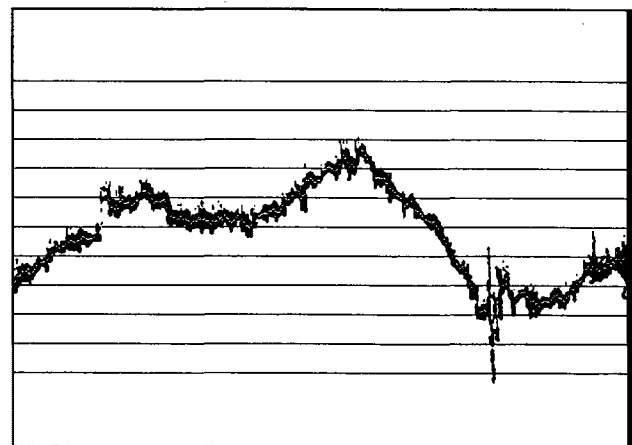


FIGURE 2 Screen display of DOS version of APPARE: scanned data (black) overlaid with extracted trace (white).

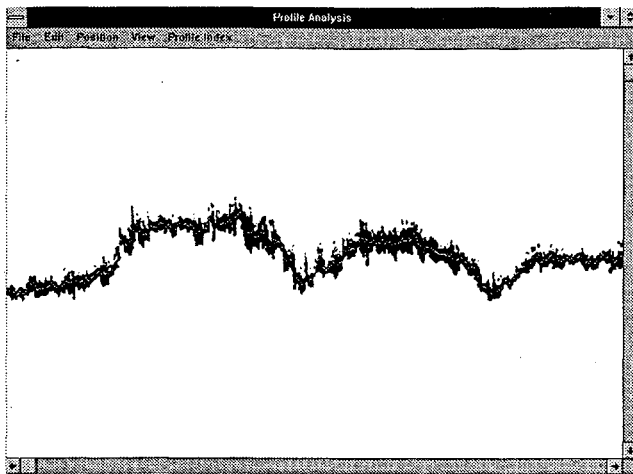


FIGURE 3 Screen display of MS Windows version of APPARE: scanned data (black) overlaid with extracted trace (white).

and end points is necessary. To facilitate such operations, an interactive graphical editor is implemented in APPARE. The editor displays the scanned profile image and provides the user with a cross-hair cursor for selecting the start and end points, an eraser for removing spurious data points, and annotating tools for writing notes on the margins of a scanned profile image.

All changes made to a scanned profilogram are saved in a hidden file, which is attached to the graphical data file for the profilogram. This feature enables the operator to recover from editing mistakes or the supervisor, who is provided with a privileged password key to the hidden file, to reexamine the changes.

Profile Trace Extraction

The profile trace produced by the profilograph strip chart recorder is not an ideal thin curve because of pavement textures, dirt and rocks on the road, mechanical vibrations, and simply the thickness of the recording pen. Thus, for manual profile trace reduction, the profile trace needs to be "averaged by drawing a line through the vertical midpoint of the trace created by the profilograph using a pen of contrasting color" (3). This procedure apparently introduces some arbitrariness into the manual trace reduction procedure. On computerized profilographs, this appears to be one of the causes for a linear digital filter to produce unsatisfactory profile reduction results (6,8).

In APPARE, this "midpoint extraction" procedure is performed on the scanned raster image to obtain the digitized vector image, that is, a single-valued function described by x - y coordinates, of the profile trace. In addition to performing the midpoint extraction, the program has to deal with imperfect scanned images such as (a) spurious noisy dots that are very close to the profile trace and (b) missing data points—that is, a gap in the scanned profile trace—that might be as small as 1/12 mm (1/300 in.) but large enough to confuse and halt the entire midpoint extraction process.

The midpoint extraction filter handles the first problem by using a moving slope threshold, based on the assumption that the slope of the road from one data point to the next cannot exceed a certain bound. The default value of this threshold is set to ± 45 degrees in APPARE, which yields satisfactory results; otherwise it can be set by the user. Once the threshold is determined, the midpoint at the current location is found within the upper and lower slope limits projected from the previous data points, as illustrated in Figure 4. One exception is at the start point, where no previous data point is available, the slope limits are projected from a fictitious previous point at the same elevation of the start point.

To cope with the problem of missing data points within the slope threshold, a cubic polynomial extrapolation algorithm is used to estimate the missing data point using the previous four data points.

The extracted profile trace is then saved into a disk file for further process. Screen snapshots of extracted profile traces overlaid on the scanned profile traces are shown in Figures 2 and 3.

Power Spectral Compensation

It is well known that the profilograph severely distorts frequency contents of the pavement elevation profile because of its periodic, bandpass frequency response and infinitely many transmission zeros (4,11,12,15). As a consequence, profilograms cannot be used to reconstruct the original pavement elevation profile (15). However, in an earlier paper (14) a mathematical model for the pavement roughness is proposed in which the roughness profile is described by an ergodic, Gaussian, and white stochastic signal (sequence), possibly superimposed with certain deterministic features. As indicated by the kinematic model for the profilograph (4,11,12,15), the profilogram consists of a linear combination (a weighted

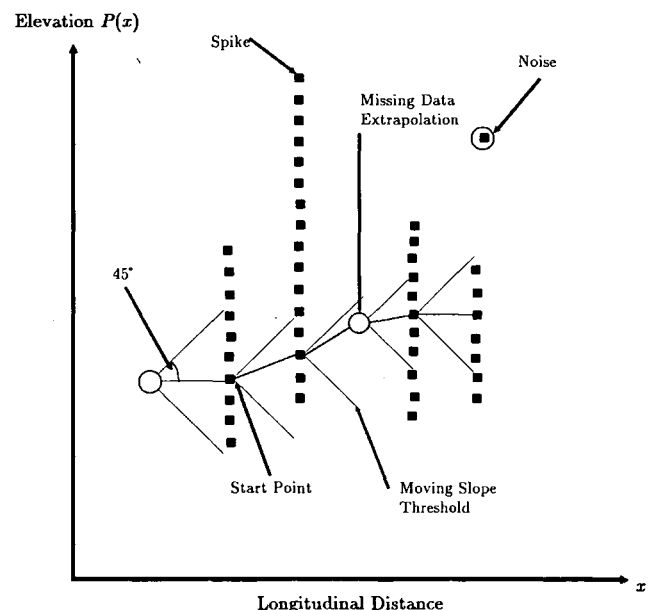


FIGURE 4 Trace extraction from scanned profilogram.

sum) of shifted input. Because the power spectral density (PSD) function of a white stochastic sequence is a constant, the profilograph can be used to characterize some stochastic features of the pavement roughness. It is, in fact, this latter property that makes the profilograph a valid profiling device (15).

To obtain a faithful statistical characterization of the road roughness, it is vital that the PSD of the profile be retained. Although it is known that the kinematics of the profilograph alters the PSD of the pavement roughness profile according to its spatial frequency response—provided that the PSD is white (15), all post data recording and processing devices, such as the pen plotter on a conventional profilograph, digital counter and filters on an automated profilograph, and even the operation speed of the profilograph, also alter the profile PSD to a certain extent (15). These problems can be compensated by a linear shift-invariant filter.

Let $p(x)$ and $q(x)$ be, respectively, the pavement profile and the measured profile through some (linear shift-invariant) profiling device having a frequency response $T_p(\omega)$. Then the power spectral density functions (PSDF) of $p(x)$ and $q(x)$ are related by

$$\Psi_{qq}(\omega) = |T_p(\omega)|^2 \Psi_{pp}(\omega) \quad (1)$$

Clearly, the measured profile is distorted by the profiling device unless $|T_p(\omega)| = 1$, which is unrealistic. Now suppose that a compensating filter having a frequency response $T_c(\omega)$ can be designed such that

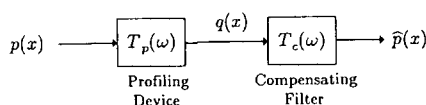
$$|T_p(\omega)T_c(\omega)|^2 \approx 1 \quad (2)$$

within the frequency band of interest $\omega_l \leq \omega \leq \omega_h$. Connect this compensating filter in series with the profiling device as shown in Figure 5 and denote by $\hat{p}(x)$ and $\Psi_{\hat{p}\hat{p}}(\omega)$ the output and its PSDF, respectively. Then the PSDF of original profile can be recovered within the frequency band $\omega_l \leq \omega \leq \omega_h$

$$\Psi_{\hat{p}\hat{p}}(\omega) = |T_p(\omega)T_c(\omega)|^2 \Psi_{pp}(\omega) \approx \Psi_{pp}(\omega) \quad (3)$$

Note that Equation 3 does not imply $p(x) = \hat{p}(x)$ at every longitudinal position x because $p(x)$ and $\hat{p}(x)$ are two random spatial signals, and Equation 2 cannot be realized for all frequencies. However, Equation 3 ensures that the two random signals, $p(x)$ and $\hat{p}(x)$, have the same statistics within the frequency range $\omega_l \leq \omega \leq \omega_h$, and these statistics can be used to characterize the roughness of the original and the recovered profile.

In addition to the profile distortions caused by the kinematics and dynamics of data recording and processing devices,



$p(x)$ = Pavement profile

$q(x)$ = Measured profile with distortion

$\hat{p}(x)$ = Corrected profile

FIGURE 5 Block diagram for profile compensating filter.

extraneous signals may be introduced during the profiling process to corrupt the profile PSD. It is found that the eccentricity of the profiling wheel of a profilograph introduces a power concentration as high as 20 db at the frequency corresponding to the circumference of the wheel (15), and misalignment in the scanning process causes excessive power concentration in the low-frequency spectrum. In APPARE, the former problem is effectively coped with by using a notch filter, and the latter is corrected by using a linear regression filter.

Detailed analysis and discussions for power spectral compensation are presented in other work (14,15). The profilograph compensating filter developed by Zhu et al. (15) is implemented in APPARE and applied to the extracted profile trace to improve validity of the PI. The principle of using a spectral compensation can be applied to any profiling instrument with linear shift-invariant dynamics. Effective design algorithms exist for designing such digital compensating filters, which are readily implemented into APPARE to process digitized profile data from computerized profilographs and other types of profiling instrument.

Roughness Index Evaluation and Conversion

The last functional component of APPARE is for roughness index evaluation and conversion. In particular, an automated BBPI algorithm is developed and implemented with satisfactory results. The IRI algorithm is also implemented. Other widely used roughness indexes are either being implemented or will be implemented using empirical or mathematical correlations.

The implementation of the BBPI algorithm follows closely the procedures adopted by the LDOTD/LTRC, as specified previously (3) for manual PI evaluation for the California-type profilograph. Because the goal is to obtain a computer implementation of the BBPI procedure, no PSD compensation is used here. The algorithm accumulates the counts of excursions beyond a ± 2.5 -mm (0.1-in.) blanking band weighted by their amplitude in increments of 1.25 mm (0.05 in.), then divides the total weighted counts by the total distance over which the profile is taken. This algorithm, although conceptually simple, turned out to be a nontrivial task. The main difficulty was to distinguish a deviation from one of the following situations according to LTRC (3):

1. "Spiked projections caused by the profilograph rolling over rocks or dirt on the pavement" are to be discounted;
2. "Small portions of the average profile trace . . . visible outside the opaque blanking band, . . . unless these projections extend 0.75 mm (0.03 inch) or more vertically and 2 mm (0.08 inch) or more longitudinally on the profile trace . . ." are to be discounted;
3. "Only the highest peak of a double-peaked scallop is to be counted;" and
4. "Scallops that fall at the end of one position of the blanking band in such a manner that they fall into two positionings of the blanking band are to be counted only once."

To accommodate these ambiguous cases, a significance test is set up in the program. Only those excursions in which the

area enclosed by the profile trace and a blanking band exceeds a certain threshold value are counted for the PI calculation. By fine tuning this threshold value to 130 mm² (0.2 in.²), an excellent correlation between the automated and manually evaluated PI was obtained on data from 27 test sites with an R^2 of 0.991. The test data are shown in Table 1 and Figure 6. The following comments are appropriate:

1. The poor reliability and repeatability of the manual BBPI procedure because of operator error can be attributed to two main factors: (a) operator negligence and (b) illusion in human visual perception. The former can be greatly reduced by carefully controlling the PI evaluation procedure, which was the case during these tests. The discrepancy shown in Figure 6 between the manually evaluated PI and APPARE-evaluated PI is mainly attributable to illusion. It is clearly seen in Figure

6 that the manually evaluated PIs for smooth roads where $PI \leq 78$ mm/km (5 in./mi) tend to be overestimated, whereas those for rough roads tend to be underestimated. This discrepancy is because human perception relies heavily on comparison with the environment, which affects the operator's judgment on the magnitude of excursions in the ambiguous cases. To appreciate this conclusion, interested readers are invited to first evaluate the PIs for the two (fictitious) profilograms shown in Figure 7 and then use a ruler to draw the 1.25-mm (0.05 in.) elevation lines between the given 2.5 mm (0.1 in.) elevation lines, reevaluate the PIs, and compare with the first evaluation.

2. Ambiguities in the BBPI evaluation other than the aforementioned four cases also exist and are considered by various highway construction agencies. For instance, the Central Federal Lands Highway Division of FHWA, Denver, also con-

TABLE 1 Computation and Correlation Results for Profile Index

LOCATION	SITE.#	PI (inch/mile)	CPI (inch/mile)	Note
LA22 SB-OL Hm	1	1.00	0.5	
LA22 SB-OL Hm	2	4.25	3.59	
LA22 SB-OL Hm	3	1.75	1.53	
LA@@ NB-OL Hm	4	0.50	0.51	
LA@@ NB-OL Hm	5	2.50	2.56	
LA@@ NB-OL Hm	6	1.25	1.02	
LA44 NB-OL JCP	7	19.55	19.07	
LA44 NB-OL JCP	8	14.75	15.04	
LA44 SB-OL JCP	9	31.00	30.21	
LA44 SB-OL JCP	10	25.20	25.49	
Burbank SB-OL JCP	11	6.60	7.25	
Burbank NB-OL JCP	12	10.31	10.88	
I-49 NB-OL JCP	13	0.00	0	
I-49 NB-OL JCP	14	2.25	1.53	
I-49 NB-OL JCP	15	3.25	2.04	
I-49 NB-OL JCP	16	2.75	1.54	
I-49 NB-OL JCP	17	5.00	3.32	
I-49 NB-OL JCP	18	2.75	2.3	
I-49 NB-OL JCP	19	1.00	1.03	
I-49 NB-OL JCP	20	2.00	1.02	
I-49 NB-OL JCP	21	5.25	5.97	1 large Bump
I-49 NB-OL JCP	22	2.00	1.52	
I-49 NB-OL JCP	23	0.25	0.25	
I-49 NB-OL JCP	24	0.25	0.25	
I-49 NB-OL JCP	25	9.14	8.89	1 large Bump
I-49 NB-OL JCP	26	8.10	6.01	
I-49 NB-OL JCP	27	5.07	2.94	
Linear Correlation of the PI and CPI:				
Regression Parameters:		Regression Results:		
Constant			-0.454	
Std Err of Y Est			0.770	
R Squared			0.991	
No. of Observations			27.000	
Degrees of Freedom			25.000	
X Coefficient(s)			1.005	
Std Err of Coef.			0.019	

PI Manually calculated Profile Index

CPI Computer calculated Profile Index

Profile Index unit conversion: 1 inch/mile = 15.6 mm/km

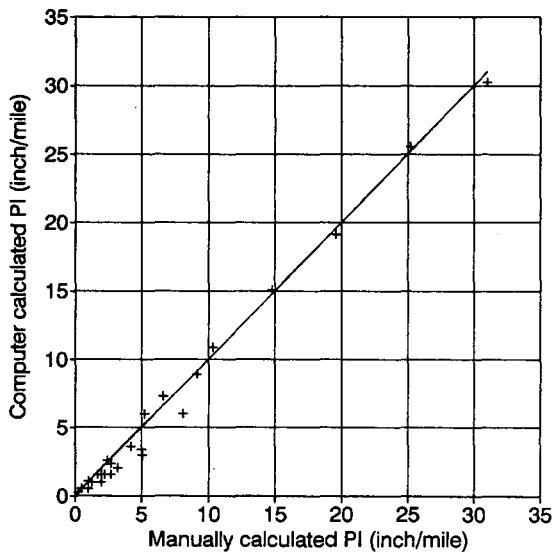


FIGURE 6 Correlation of computer calculated PI and manually calculated PI (see Table 1 for correlation results).

siders the situation in which “a scallop is incomplete at the end of a blanking band position but does not continue into the subsequent position.” Thus, the definition and judgment of such ambiguities constitute another major factor for the poor reliability and repeatability of the BBPI procedure. Clearly, this problem cannot be resolved by computerized BBPI algorithms. In this regard, a new statistical profile index algorithm described in a revised paper of Zhu (14), which computes the mean deviation (MD) of the profile trace from the blanking band and is therefore called MDPI, appears to be a superior alternative.

In a recent study (7) on the accuracy and variability of the profilogram trace reduction, the PI evaluated by APPARE

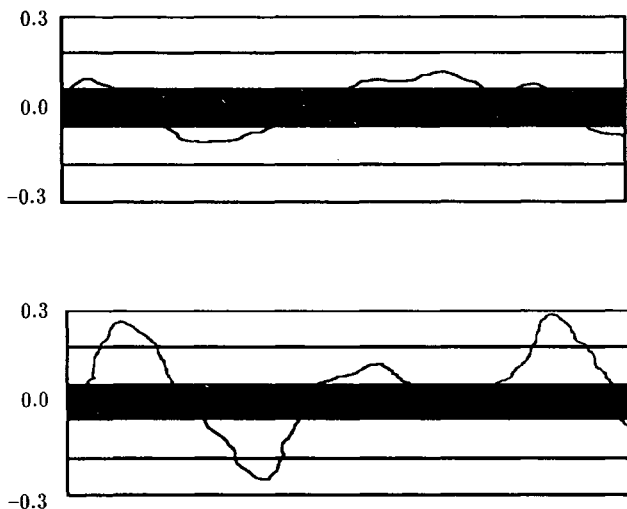


FIGURE 7 Demonstration of illusion in manual PI evaluation.

compared favorably with the PI evaluated by 23 operators, among whom 8 were considered experienced operators, and by two commercially available computer programs.

SUMMARY AND CONCLUSIONS

APPARE is a newly developed software package for automated pavement profile analysis and roughness evaluation. It has a user-friendly graphical user interface and self-contained profile analysis functionalities. Salient features of the software include (a) a desktop scanner-based, midpoint profile trace extraction profilogram digitizer; (b) power spectral compensating filter for profile corrections; and (c) successful computer implementation of the BBPI algorithm. The standard IRI algorithm is also implemented in APPARE, along with other widely used roughness indexes.

The basic functionalities of APPARE are now fully operational. In the future, facilities to handle the power spectral analysis of pavement profiles, rideability analysis, and simulations and other commonly used roughness index algorithms will be developed and implemented in the software.

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