	Cost per Mile Tested ($)
Personnel	1.00
Meals and lodging	0.40
Automobile mileage	0.45
Supplies	0.05
Total	1.90

These costs were experienced in a statewide, primarily rural test program, using 4-day, 40-hr workweeks. On the average, slightly more than one-half of the total mileage driven was tested.

The cost of computing roughness ratings and entering the data into the central data base is less than $0.40 per mile tested, including both personnel cost and mainframe computer charges.

Maintenance Cost

It is difficult to estimate average system maintenance costs based on one year's experience. In that time, one of the microcomputer's floppy disk units required replacement at a cost of $400; because the linear accelerometer was dropped in the laboratory, it required $200 to repair. Finally, a transistor in the 115-V AC inverter was replaced at a cost of $20.

Routine replacement of the ultrasonic transducer is required because of accumulation of dirt on its surface. During the year, two replacements were made at a cost of $30 each. No other periodic system maintenance is required, nor is extra vehicle maintenance necessary.

CONCLUSION

The profilometer developed by the South Dakota Department of Transportation has proved to be an efficient instrument for economically measuring pavement surface roughness independent of test vehicle characteristics. Because of the system's speed and high level of automation, it is the intention of the Department to use it to perform annual statewide roughness surveys and to continue to determine construction priorities based largely on the measurements obtained.

Development of a Data Acquisition Method for Noncontact Pavement Macrotexture Measurement

INNCHYN HER, J. J. HENRY, and J. C. WAMBOLD

ABSTRACT

Pavement texture is the controlling factor in the skid-resistance level of roadway surfaces. To obtain more complete data on texture, a noncontact high-speed method was developed to permit the collection of pavement data from a vehicle moving at highway speeds. This method combines existing designs with new processing concepts and hardware improvements and is believed to be promising for the measurement of macrotexture. The system uses a light-sectioning technique in which a strobed band of light with high infrared content is projected onto the pavement. A camera with high sensitivity to the infrared portion of the spectrum views the band at an angle. The pictures resulting from each strobe are stored in a frame grabber and subsequently processed by detecting the shadow along the leading edge of the band to produce a macrotexture profile. The method was evaluated using a prototype system operated both in the laboratory and in the field at 40 mph. The results are encouraging, and recommendations for improvement are made that will result in a practical noncontact macrotexture profile acquisition system.

It is generally agreed that the skid resistance of a pavement is controlled by the surface texture characteristics. Therefore, by measuring the relevant parameters describing texture, or by measuring a physical process dependent on texture, regression techniques can be applied to relate skid resistance to the chosen texture parameter or process. Two scales of texture are of particular importance, microtexture and macrotexture. Pavement microtexture is the deviation of a pavement surface from a true planar surface with characteristic dimensions of wavelength and amplitude less than 0.5 mm. Pavement macrotexture is the deviation of a pavement surface from a true planar surface with characteristic dimensions of wavelength and amplitude from 0.5 mm up to those that no longer affect tire-pavement interaction (1).

A number of pavement texture measurement systems are currently in use or are under development both in the United States and abroad. However, they are still not adequately reliable, are expensive, and are not easy to operate. A project was conducted at the Pennsylvania Transportation Institute to develop a prototype high-speed, noncontact texture measurement technique for both microtexture and macrotexture. The system had to be inexpensive, self-sufficient (which implies that some decisions must be made automatically), and capable of being operated from a moving vehicle at normal highway speeds. Be-

TABLE 1 Comparisons of the Rating Score Levels and Capabilities of the Recommended Texture Measurement Systems

	Measurement				Rating Score Levels				
	Macrotexture		Microtexture						
Recommended Texture Measurement Systems	Direct	Indirect	Direct	Indirect	Technical Feasibility	Operational Feasibility	Cost Score	Functional Feasibility	Cost-Effectiveness
Ensco vidicon system	X				High	High	Medium	Highest	Medium
Ribbed versus blank tire skid-test concept		X		X	High	High	High	Medium	High
Light depolarization		X			Medium	High	High	Medium	Medium

cause the system was expected to measure the texture profile down to about one-half of the lowest wavelength for the macrotexture, high-resolution hardware was required.

BACKGROUND

Many noncontact measuring techniques have been developed and evaluated during the past decade (2), but most are not suitable for operation on a moving vehicle (3). Table 1 presents comparisons of the rating score levels and capabilities of three feasible basic systems. Among them, Goodman's method (4) was considered the most promising system for a noncontact scheme for the high-speed acquisition of pavement texture data. This scheme consists of forming and directing an extremely narrow, fan-shaped, stroboscopic light beam vertically downward onto the surface, and detecting the resultant single-line profile with a camera viewing the light beam at an angle.

In 1976 Goodman's experiments were repeated and enhanced with computerized image processing facilities for the Maryland Department of Transportation (5). The system used a high-intensity, short-duration flash of light projected vertically onto the pavement through a very thin optical slit. The resulting image on the pavement was a fine line approximately 100 mm long and 0.25 mm wide. The sampling frequency was 10 Hz, which provided a reading every 1.8 m at a vehicle speed of 40 mph. The results had a very poor resolution and were restricted to relatively low vehicle speeds, typically below 40 mph. Blooming of the video image was a serious problem whenever an adjustment to the system was required to compensate for the lack of contrast between the image and the background, caused by high levels of ambient light and by the pavement color. The pavement being measured had to be fairly smooth in order to minimize the vertical motion of the vehicle so that the optics of both the projecting system and the television camera were in proper focus. It was also reported that the system should be operated at night, because the thin slit of light projected on the pavement tended to be masked by the ambient illumination.

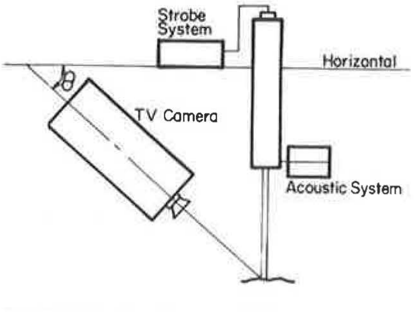


FIGURE 1 Profile acquisition system—schematic.

PROPOSED SCHEME

To overcome the limitations of existing techniques, much effort has been directed in the past few years to develop methods that embrace new concepts and existing designs. Figures 1 and 2 show the basic concept composed of several separate subsystems that are described individually in the following paragraphs.

Strobe System

The entire system is designed to be operated from a vehicle moving at a highway speed of at least 40 mph, or about 25 mm per millisecond. In order to freeze a picture at these speeds, with no more than

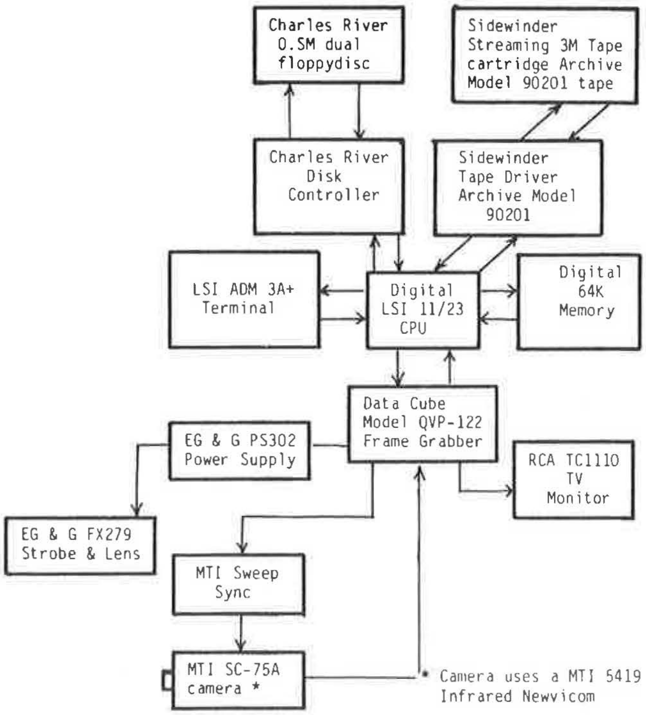


FIGURE 2 Profile acquisition system—block diagram.

a one-half-millimeter smear (the required tolerance for macrotexture), a stroboscopic light source with a flash duration as short as 20 microseconds is required. A bulb-type xenon flashtube (EG & G Fx-201) was selected for the prototype version of the system design, although a linear xenon flashtube is suggested for further improvement of the prototype. The entire spectral output of the flashtube is not useful because only the near-infrared range is used. To ensure that the system functions well during daylight as well as at night, image inputs are filtered to pass only the near-infrared before they enter the television camera to improve the contrast (S/N ratio) between the profile and the background. Figures 3 and 4 show the average daytime background radiation spectrum and the power spectrum of the present flashtube. Less than 20 percent of the flashtube output passes through the present filter (Figure 5), a waste of energy that could be reduced by using a more suitable infrared source.

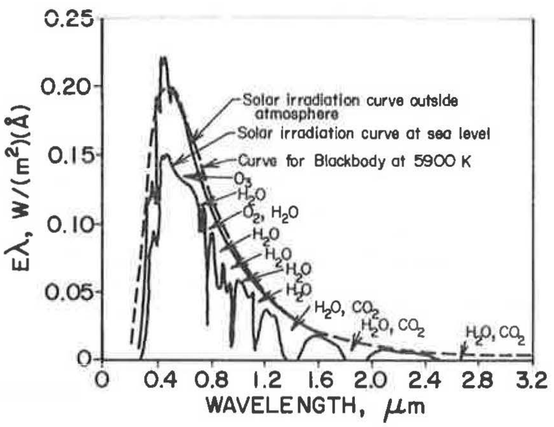
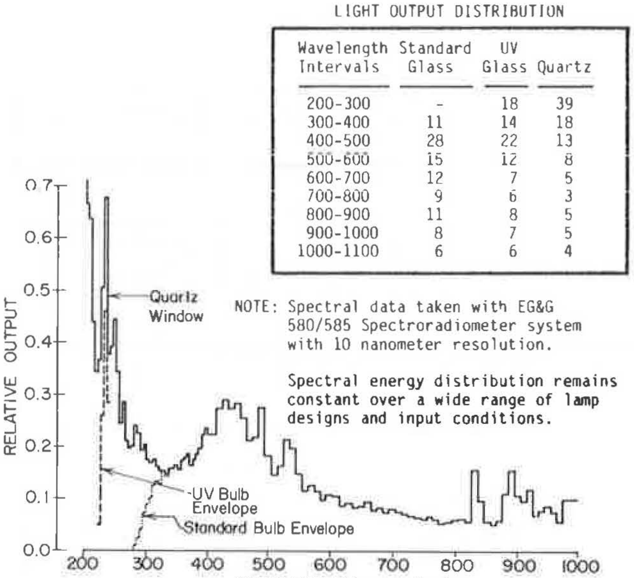


FIGURE 3 Spectral distribution on the sun.



LIGHT OUTPUT DISTRIBUTION

Wavelength Intervals	Standard Glass	UV Glass	Quartz
200-300	-	18	39
300-400	11	14	18
400-500	28	22	13
500-600	15	12	8
600-700	12	7	5
700-800	9	6	3
800-900	11	8	5
900-1000	8	7	5
1000-1100	6	6	4

NOTE: Spectral data taken with EG&G 580/585 Spectroradiometer system with 10 nanometer resolution.

Spectral energy distribution remains constant over a wide range of lamp designs and input conditions.

FIGURE 4 Spectral distribution for a bulb-type flash lamp.

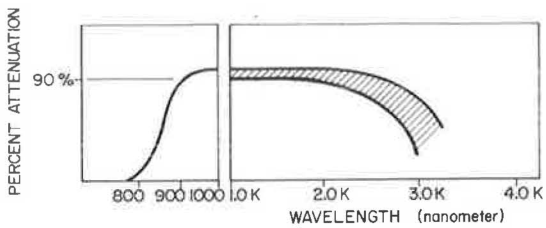


FIGURE 5 Characteristics of filter used in the profile acquisition system.

Optical System

The light source generated by the flash tube is collected, directed, and focused to form a concentrated strip of light on the pavement. To achieve this, the optical system is composed of a concave reflection mirror that makes use of the upward light beams, a pair of optical condensers, a sharp-edged band slit (no longer a thin slit), pairs of projection lenses, and some adjusting mechanisms. Several arrangements were incorporated to increase the performance of the optical system. First, the position of the condensers was accurately adjusted so that a semi-focused image of the discharging arc of the strobe was formed on the slit. Instead of forming an evenly illuminated disc on the slit, this method allows for a concentration of the light to pass through the slit. Second, a pair of orthogonal cylindrical lenses was implanted in front of the projection lenses.

The effect of the cylindrical lenses is to permit linear expansion of the projected image only in the desired direction, and thus refine the sharpness of the edges of the slit. Because the output of the whole system is filtered before it enters the television camera, the chromatic aberration, which is usually inevitably associated with wide-band continuous light sources passing through different media, is therefore reduced to a negligible amount.

Acoustic System

This system, which provides a major technical advance over other existing designs, serves as a system synchronizer to continuously provide synchronization signals to each subsystem processor; it gives commands to other systems while it detects suitable conditions for taking pictures, for example, when each subsystem is ready and the picture is in focus. It is equivalent to a built-in automatic focusing device that relieves the television camera and the optical system of the constraint of having a large depth of focus. This provides an advantage of higher magnification for the acquisition system, and thus consequently permits a higher degree of precision to be obtained with the entire system (6).

Television Camera

Because the system is required to process low intensity pictures, due to the filtering effects and the short duration of the stroboscopic light source, an extremely light-sensitive camera with the ability to capture short-duration images is required. An infrared-enhanced Newvicon camera (MTI 75 series) was used with a 2-in., f/10 close-up lens. Charge-coupled device (CCD) cameras were considered early in the development of the system, but were rejected because they do not have the desired infrared sensitivity. Because the television camera has analog resolution along each raster line, analog signals represent more important information, which, in this case, is

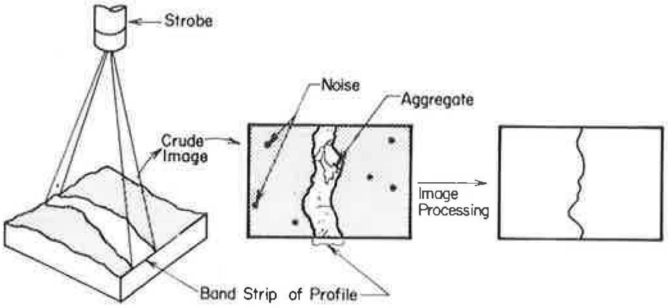


FIGURE 6 Picture acquisition.

the amplitude of the pavement texture. The camera was mounted in the system in such a way that a 2-in. slit on the pavement could be displayed vertically on the screen of the television monitor. With the aid of the acoustic system, the depth of the focus of the television camera was reduced to as small as 0.25 in., and the camera will take pictures only when it is in focus.

Frame of the System

The mechanical supporting frame must be rigid because only a small amount of relative motion can be tolerated between the components of the system. It is also designed to allow easy adjustment, both vertically as well as horizontally, to allow for possible changes of tire inflation and pavement roughness, and for routine maintenance of the system. The frame is mounted perpendicular to the direction of the vehicle, and the slit is positioned to be in a wheel track. The design provides easy mounting of the frame and promises less profile smear and more accurate results than the other alternatives that were considered.

PICTURE PROCESSING

After the television camera has taken a picture containing a pavement line profile, as shown in Figure 6, a series of image processing techniques is applied to obtain usable data and reasonable interpretations of the pictures. These procedures are digitization, preprocessing, profile refinement, and postprocessing. Each of these procedures is discussed below.

Digitization

To analyze and translate the raw analog outputs from the television camera, an image digitizer is needed to provide readable formats for the processors. For the first version, two cards of the high-speed frame grabber (Datacube QVG-120/QAF-120) with 320h*240v resolution and 256 black-and-white intensity on each picture element, were linked to a minicomputer (Digital LSI-11/23). These cards enable the system to process pictures at a speed of less than 5 seconds per picture or, equivalently, 15 to 20 processed profiles per mile of highway pavement.

Preprocessing

Trimming

After digitization, the picture is stored pixel-by-pixel in the random access memory of the frame grabber. Before the profile is taken out and transmitted into the core of the minicomputer for refinement, it is suggested that some preprocessing be performed to help eliminate unnecessary transmission. Figure 7 shows that while the vehicle bounces slightly up and down within the depth of focus of the acoustic system, the image moves from left to right on the monitor. It is clear that there are limits for horizontal pixel coordinates where the acoustic system shuts off the trigger signals. It is straightforward to calculate the limits and to program the frame grabber to transmit only the picture elements located between the bounds. This process reduces some of the noise by eliminating spikes, which sometimes are indistinguishable from data points.

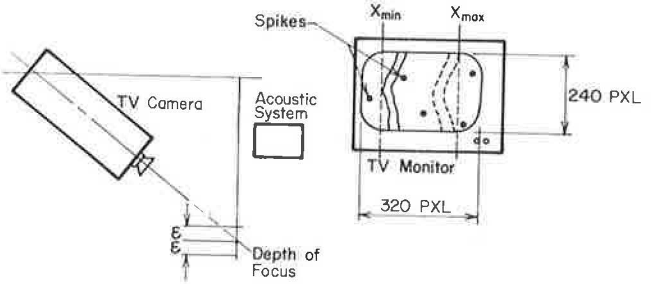


FIGURE 7 Effect of variations in range.

Thresholding

Thresholding is one of the simpler kinds of image-processing techniques. By simply discarding the points for which the intensities are below a certain level, as shown in Figure 8(a) and (b), a rough profile of the picture with some remaining noise is obtained. The threshold level need not be very close to the peak intensity of the profile, as shown in 8(c). Because the distance between the threshold point and the actual profile position is almost constant (with deviation less than dx/2, where dx is the distance between two horizontal picture elements), tracing along the threshold points could be regarded as equivalent to tracing along the actual profile, with only very small errors. Although it may appear that there is great latitude in setting the threshold level, the contrary is true in most cases. Because pavements are usually composed of multicolor textures and aggregates, as shown in parts 8(d)-(f), it is a tedious task to find the right threshold level in various background illumination conditions such that the algorithm traces neither along the edges of dark stones [TS' as shown in 8(e)] nor along the edges of bright stones (TS").

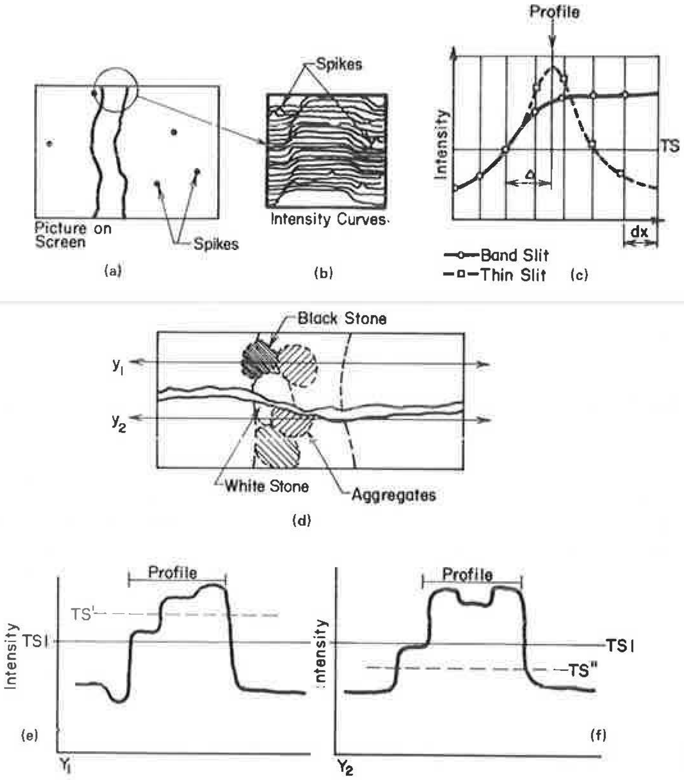


FIGURE 8 Thresholding: (a) picture on screen; (b) intensity curves; (c) threshold level; (d) effect of color of aggregate on pictures; (e) profile for section Y_1; and (f) profile for section Y_2.

An automated thresholding technique will be discussed in the recommendations.

Profile Refinement

A typical result of the system is shown in Figure 9. The raw profile, after thresholding the video output at 80 percent of the maximum intensity (that is, a value of 200 out of 256 maximum) is presented in 9(a). Note that there are several noise points and a few extra segments shown in this figure. The profile as originally generated already displayed discontinuity because the light strip was not evenly illuminated and because the discharge arc moved, due to the intensity of the bulb-type flash system in the prototype. Almost all the noise is removed as shown in 9(b), because the program allows no more than one data point on each horizontal line. By setting a reasonable value for the maximum slope in the preprocessing algorithm, the next processing step [as shown in 9(c-1) and 9(c-2)] is essentially free of all noise. It should be noted, however, that this processing procedure can affect the profile continuity in some cases. The final profile is then created by connecting the remaining points, as shown in 9(d). Line generation is a common technique for which many complete algorithms can be found (7). This final profile is clean-looking and has an accuracy directly proportional to the resolution of the entire system.

Postprocessing

It should be noted that postprocessing procedures are not usually programmed to run in real time with the acquisition system working on the highway. In practice, sequential-access memory peripherals are used to record the processed profiles via parallel logic connections. There are many post-processing techniques available to analyze image profiles. An existing quasi-pattern-recognition scheme developed

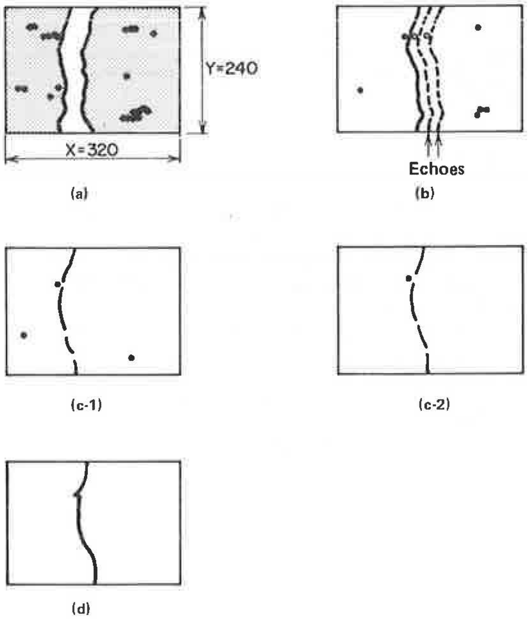


FIGURE 9 Steps in profile refinement.

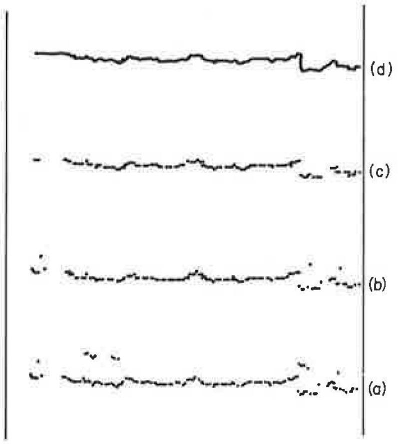


FIGURE 10 Steps in profile refinement for an actual sand surface: (a) raw data; (b) after rejection of outliers; (c) after slope limitation criteria; and (d) final profile.

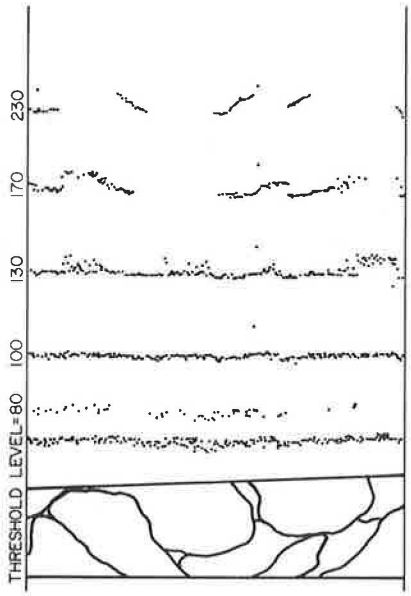


FIGURE 11 Effects of threshold level on raw profile data.

at the Pennsylvania State University was examined for application, but only a small portion of this scheme was directly applicable to this project. Other commonly used profile manipulation techniques include simple root-mean-square (RMS) computation, fast Fourier transformation, and least-square curve processing, but they were not included.

RESULTS AND CONCLUSIONS

A typical result of the system is shown in Figure 10. A raw profile after thresholding the video output at 80 percent (200/256 maximum) of maximal intensity is represented in 10(a). There are some noise points and a few extra segments shown in the picture. The profile is discontinuous because the light strip is not evenly illuminated and also because the discharging arc moves as a result of the instability of the bulb-type flash tube. Almost all of the noise is removed in 10(b) because the program allows no more than one data point on each horizontal line. By setting a reasonable value of MaxSlope in algorithm Clean, 10(c) is expected to be free of noise, although these procedures sometimes affect the profile continuity. The final profile is clean and has an accuracy directly proportional to the resolution of the entire system.

Figure 11 shows an interesting relationship between picture quality and the threshold level in measuring a sample with aggregates having a wide range of color variation. How the sample looked on the television monitor screen is shown in 11(a). There are many kinds of aggregate in which infrared reflecting ability may vary over a wide range. By changing the threshold level, the results are dramatically altered. But if the threshold level is too high, the program follows the more highly reflective stones and the picture no longer represents a line profile of the pavement texture.

Compared with the actual profile of the pavement texture, the results turned out to be quite credible. As shown in Figure 12, the main difference in appearance between the actual profiles and the processed optical results is due to the low resolution of the prototype frame grabber and the unavoidable high-frequency noise generated by the power system of the strobe. A comparison of the RMS values of several different typical core samples, obtained with a contact profiler and the noncontact prototype system, is given in Table 2. This table gives only a rough indication of the capabilities of this system, because the core samples were moved at high speed under the stationary system to simulate actual conditions on a highway. It was difficult to detect accurately on what part of the sample the system took a measurement. Also, the calculated RMS value from the results of the prototype system represents only a particular local texture (2 in. long) of the sample. To obtain as full an RMS range representation

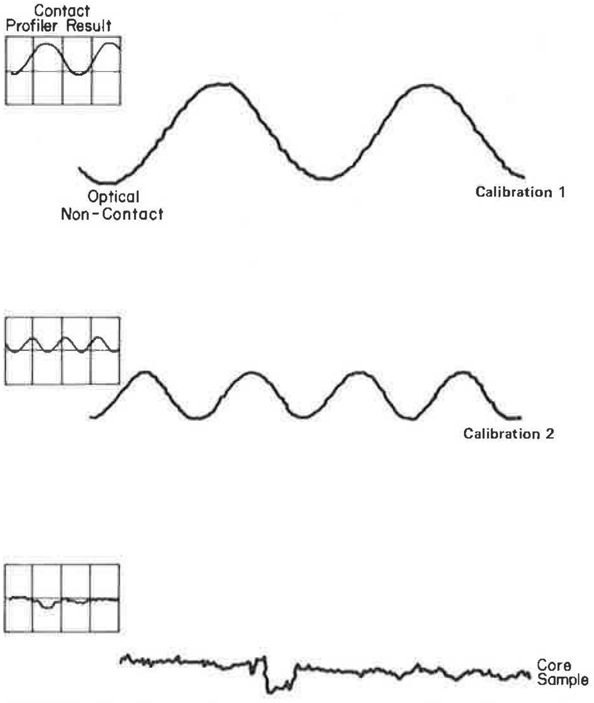


FIGURE 12 Comparison of noncontact profile with actual profile obtained by a contact profile for two calibrated samples and a core sample.

TABLE 2 Comparison of RMS Values of Seven Samples Using a Contact Profiler Versus the Noncontact Prototype

	RMS Value in mm	
Sample	Contact Tracer	Prototype
1	0.374 to 0.497	0.388
2	0.951 to 0.968	0.438
3	0.847 to 1.014	0.819
4	0.447 to 0.550	0.570
5	0.597 to 0.769	0.693
6	1.188 to 1.490	1.274
7	0.831 to 0.922	0.959

as that obtained with a contact profiler, the results of a sequence of measurements of a sample must be integrated. A positive side effect of moving the samples is that the background texture is blurred and consequently the contrast level of the data signals is increased.

RECOMMENDATIONS

The techniques presented here are by no means a complete solution for measuring pavement microtexture and macrotexture. Improvements in this method, currently being developed at the Pennsylvania Transportation Institute, are as follows:

The hardware system should include a fast microcomputer with hard disk and/or magnetic tape storage capability, a fast, high-resolution picture acquisition system, a strong and steady infrared light source (which can be achieved by using a properly designed linear Kr or Xe flashtube), and a robust, adjustable design of the mechanical supporting frame.

Some work is being done in developing an automated method to choose the optimal threshold level for the frame grabber. The aim is to take a calibration picture each time at the beginning of a run before any real profile is processed. Because correct information on the calibration texture has been stored in memory before the testing, the computer can automatically compare the results and improve the threshold level until it detects when the processed profile matches the stored values. Another possible improvement is to increase the picture resolution by interpolation. Although in this design the computer is no longer connecting the "peaks" of each raster scan to constitute the line profile [as shown in Figure 8(c)], an interpolation routine (for example, cubic spline) can still help to determine at which position the threshold occurs. By expressing the discretized intensity levels by a continuous approximation, better resolution can be obtained. Recommendations for other refinements to the prototype system can be found in Wambold and Henry (8).

ACKNOWLEDGMENTS

This paper is based on a research study conducted at the Pennsylvania Transportation Institute, Pennsylvania State University, under the sponsorship of the Federal Highway Administration, U.S. Department of Transportation. A full discussion of the study may be found in the final report for the project.

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