Status of the South Dakota Profilometer

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During 1981-1982, the South Dakota Department of Transportation (SDDOT) developed a low-cost profilometer system to replace its response-type roughometer. Since then, the unit has been used to conduct annual statewide profile surveys primarily for pavement management purposes. In September 1984, SDDOT participated in the University of Michigan Transportation Research Institute (UMTRI) Road Profilometer Meeting. The UMTRI draft report of October 1985 showed that the performance of the SDDOT profilometer was deficient in two respects. First, the beginnings of measured profiles showed extraneous long-wavelength content. Second, the system underestimated the profile magnitudes generally, but most severely on smooth highway sections, at lower test speeds, and at longer wavelengths. After the draft report was reviewed, the system was examined to determine whether these deficiencies were symptoms of inherent system shortcomings, or whether they resulted from correctable implementation errors. The errors were in fact determined to be correctable, and the system was modified accordingly. In addition, other changes have been made to allow rut depth measurement and visual rating of highway condition parameters to occur simultaneously with profile measurement.

In 1981–1982, the South Dakota Department of Transportation (SDDOT) developed a low-cost, high-speed road profilometer that has been used to conduct annual statewide surveys for highway roughness evaluation. In 1984, SDDOT was invited to participate in the University of Michigan Transportation Research Institute (UMTRI) Road Profilometer Meeting. The tests, summarized in an UMTRI draft report of October 1985 (1), showed the profilometer performance to be deficient, first because the beginnings of recorded profiles tended to exhibit extraneous long-wavelength content, and more important, because the system tended to underestimate profiles, especially on smooth highway sections, at low test speeds, and at long wavelengths.

After discovery of these problems, SDDOT initiated a complete reexamination of the profilometer system to determine their cause. The purpose of this paper is to describe the profilometer system in greater technical detail than has been published previously (2), explain the causes of the problems cited in the draft report, and describe modifications that have been made both to correct the problems and to extend the usefulness of the system.

DESCRIPTION OF PROFILOMETER

The SDDOT profilometer is an inertial profilometer—that is, it uses an accelerometer to establish an inertial reference plane from which vertical deviations in vehicle displacement are measured. A roadway profile referenced to this plane may be computed as the difference between this displacement and the distance between the vehicle and the pavement.

Conceptually, profile measurement can be divided into the six operations summarized by Figure 1: measurement of the vertical displacement of the vehicle as a function of time; measurement of the horizontal distance the vehicle has traveled; measurement of the vehicle's height above the pavement surface at equally spaced intervals of highway distance; synchronized subtraction of the vehicle displacement and height measurements to compute the relative highway profile; storage of the computed profile on magnetic media; and reconstruction of a filtered profile from the stored profile for purposes of inspection or analysis. The first five operations are performed in real time, as the test vehicle drives down the highway at normal traffic speeds. Profile reconstruction and analysis are performed after the data are returned to the laboratory.

Vehicle Displacement Measurement

Although direct measurement of the test vehicle's vertical displacement through space is impractical, it is possible to measure its vertical acceleration as a function of time and then doubly integrate the acceleration to generate the displacement record. A Schaevitz model LSBC-2 linear servo accelerometer measures the vehicle's vertical acceleration. The unit is biased for 1 g to eliminate the acceleration due to earth's gravity from the signal output. Its range of $\pm 2 g$ and frequency response of 0 to 110 Hz are adequate to measure significant vehicle motions in the range of $\pm 1 g$ at 0 to 5 Hz.

Besides the significant accelerations, the acceleration signal contains higher-frequency components corresponding to extraneous vibrations in the vehicle body. A low-pass, linear phase filter is used to attenuate these components before the acceleration signal is digitized. According to the Nyquist criterion of sampling, the acceleration signal must not contain any frequency components higher than one-half of the 125-Hz sampling frequency used by the profilometer. The filter should, however, pass the frequencies of interest with as little attenuation as possible. A Frequency Devices Model 757L8L 20-Hz eight-pole filter is mounted on a printed circuit card located within the profilometer computer, along with an operational amplifier that multiplies the acceleration signal by a factor of two to increase the signal level to 5 volts per g. The same card contains a bipolar 15-volt power supply module that powers the accelerometer, filter module, and operational amplifier.

Figure 2 shows the attenuation and delay introduced by the low-pass filter. Below 2 Hz, where the most significant vehicle accelerations occur, the signal loss is less than 0.7 percent. At 4

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Vehicle Displacement Measurement	Vehicle Distance Measurement	Vehicle Height Measurement			
accelerometer ↓ 20Hz lowpass filter ↓ analog/digital converter ↓ digital highpass double integrator	transmission magnetic pickup frequency multiplier 16-bit counter	ultrasonic transducer ↓ 16-bit timer			
Ļ	ţ	Ļ			
Software Synchronization of Vehicle Height and Vehicle Displacement, Profile Computation					
	sprucement, roorr	e computation			
Storage of C	omputed Profile on	Floppy Disk			

FIGURE 1 Profilometer block diagram, listing major hardware and software components. All processes except the last are done in real time, as the test vehicle drives at normal highway speed.

Hz, the high edge of possible vehicle motion, the loss is approximately 2.7 percent. At 20 Hz, the signal is attenuated by 50 percent, and at the Nyquist frequency of 62.5 Hz, the signal is attenuated by 99.95 percent. The delay introduced by the filter is approximately 25.3 msec and is essentially constant for signals in the frequency range of 0 to 40 Hz, decreasing to 12.3 msec at 62.5 Hz.

After the acceleration signal is filtered, it is converted into numbers that may be manipulated by the profilometer computer. An ADAC Model 1012 12-bit analog-to-digital converter installed in the computer samples the signal at 8-msec intervals, converting signal levels between -5 and +5 volts (corresponding to accelerations of -1 and +1 g) into integers between -2047 and +2047. The resolution of the acceleration signal is 1 g divided by 2048, or 0.01571 ft/sec². The analog-to-digital converter's stated accuracy is ± 0.025 percent of full scale reading, or approximately one-half of the resolution.

Acceleration sampling must occur at precisely timed intervals to ensure accuracy in the subsequent integration. Measurements are initiated by an ADAC Model 1601GPT clock programmed to generate interrupts at intervals of 8.000 msec. The clock is equipped with an error flag to indicate whether interrupts are being serviced by software as quickly as they are being generated. Profile measurement software monitors the flag and would abort profile measurement if an error were detected. Tests have shown that the profilometer hardware and software are capable of sustaining the 125-Hz sampling rate under every conceivable operating condition. The digitized acceleration signal is doubly integrated to yield a record of vehicle displacement. The SDDOT profilometer integrates numerically rather than with electronic circuits in order to avoid problems of integrator saturation.

The growth of errors due to offsets is a problem inherent to both analog and numerical integration. When an acceleration signal composed of a true acceleration a(t) plus some offset b is doubly integrated, the computed displacement $u^*(t)$ consists of the true displacement u(t), one error term linear in time due to the initial (unknown) vertical velocity, and another error term proportional to the square of time t^2 . That is,

$$u^*(t) = u(t) + v(0)t + 0.5bt^2 \tag{1}$$

For even small values of offset b, the second error term predominates as time increases. For a profile 10 mi in length, the value of t^2 exceeds 0.5 million sec² assuming a test speed of 50 mph. Even for an offset of only 10^{-3} g, the displacement error is approximately 8,300 ft, more than 1.5 mi, in elevation. Although the error term involving initial velocity is proportional to time and grows more slowly, it, too, can overwhelm the true displacement. Fortunately, because both error terms vary slowly, they may be controlled by removing very low frequencies from the integrated displacement signal.

A numerical process, a type of digital filter, has been devised to both doubly integrate and high-pass filter the acceleration signal as it is being measured. It is useful to describe the filter's performance in terms of transfer functions that define ratios of

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FIGURE 2 Characteristics of the eight-pole, linear-phase, 20-Hz low-pass antialiasing filter used to condition the accelerometer signal.

its output to input within the frequency range of interest. The composite transfer function can be expressed as the product of an integration transfer function I(f) and a high-pass filtering transfer function H(f), where f is the frequency of the signal:

$$F(f) = I(f) * H(f) \tag{2}$$

The ideal double integrator transfer function

$$D(f) = -(1/2\pi f)^2$$
(3)

is numerically approximated by the transfer function

$$I(f) = -[h/2 \sin (\pi f h)]^2$$
(4)

The quality of this approximation depends on the signal frequency f and the sampling interval h; the ratio of actual to ideal integration is given by the relation

$$R(f) = I(f)/D(f) = [\pi f h/\sin(\pi f h)]^2$$
(5)

which is exactly 1 for a frequency of 0, but reaches a maximum value of 2.47 when the frequency equals the Nyquist frequency (one-half of the sampling frequency). At 5 Hz, below which vertical acceleration signals of interest lie, the approximation overestimates the displacement magnitude by 0.5 percent. Although the integration increasingly overestimates at high fre-

quency, the low-pass antialiasing filter so strongly attenuates with increasing frequency that no net overestimation occurs. The high-pass filtering transfer function is

$$H(f) = 1/[1 + \cot^2(\pi f h)/\cot^2(\pi f_0 h)]$$
(6)

which has complete attenuation at zero frequency, 50 percent attenuation at the cutoff frequency f_0 (0.01 Hz for the profilometer system), and no attenuation at the Nyquist frequency. Because the transfer function is only second order, the filter does not exhibit sharp roll-off. Its performance is sufficient, however, to limit the growth of integration errors.

The combination of integration and high-pass filtering is accomplished by a second-order recursive digital filter of the form

$$u_n = Au_{n-2} + Bu_{n-1} + Ch_2 a_{n-2} \tag{7}$$

where the constants A, B, and C are determined analytically from the sampling interval h and the cutoff frequency f_0 . That is, the displacement u_n is given as a linear combination of the two previously computed displacements u_{n-1} and u_{n-2} and the acceleration a_{n-2} measured two sampling intervals previously.

The integration algorithm introduces a signal delay of two sampling intervals at all frequencies, so that the computed displacement at time t actually corresponds to the vehicle displacement two intervals earlier. In addition, the high-pass filtering introduces delay that increases rapidly as frequency decreases. Thus, longwave vehicle displacement components are shifted significantly.

Figure 3 shows the composite effect of the high-pass double integration, assuming a vehicle speed of 55 mph. The gain ratio—that is, the ratio of computed displacement to true displacement—varies within ± 2 percent over the frequency range of 8 to 0.0 Hz, corresponding to wavelengths of 10 to 1,000 ft. At frequencies greater than 1 Hz, the signal delay is nearly constant and equal to a distance equivalent to two sampling intervals, or about 1.3 ft. At lower frequencies, the signal delay increases significantly; at a frequency of 0.0114 Hz, corresponding to a wavelength of 7,000 ft, the signal delay exceeds 1,000 ft.

The practical significance of Figure 3 is that for the sampling frequency, high-pass frequency, and vehicle speed normally used by the profilometer, the high-pass integration accurately estimates the amplitude of vehicle motion at wavelengths up to 1,000 ft, although not without phase distortion and delay at longer wavelengths. Because the vertical motion of the vehicle is restricted to frequencies less than 5 Hz, the integration's overestimation at higher frequencies is not significant.

Because the integration and filtering are based in time rather than distance, lower vehicle speeds alter the wavelength and delay distances. Figure 4 is similar to Figure 3, except that a slower vehicle speed is assumed. As expected, the range of accurate operation is altered in proportion to the ratio of vehicle speeds.

Vehicle Distance Measurement

Accurate determination of the horizontal vehicle travel is required to ensure correct data location. A magnetic pick-up mounted between the profilometer vehicle's transmission and speedometer cable generates electronic pulses at 0.873-ft intervals. At any speed greater than 5 mph, a frequency multiplier located on an interface board within the profilometer computer multiplies the pulse frequency by 512, improving the distance resolution to 0.00190 ft per count. The interface board accumulates these counts in a 16-bit counter until the count matches a software-programmable count equivalent to the desired data interval, then generates a program interrupt that causes the software to accumulate the distance, initiate vehicle height measurement, and compute profile. Normally, an interval of 1.0 ft is specified, but other intervals may be selected so long as they are consistent with the operating speed of the system.

Calibration is determined automatically by measurement of the number of counts required to travel a known distance, allowing periodic adjustment to correct for tire wear.



FIGURE 3 Gain ratio (defined as the ratio between amplitudes of computed and true displacement) and signal delay of digital high-pass double integrating filter at 55 mph.



Highpass Integrator Performance, 27mph

FIGURE 4 Gain ratio (defined as the ratio between amplitudes of computed and true displacement) and signal delay of digital high-pass double integrating filter at 27 mph.

Vehicle Height Measurement

The distance between the accelerometer location and the pavement surface is measured by an ultrasonic ranging device based on an instrumentation quality version of the electrostatic transducer used on autofocusing Polaroid cameras. The principle of operation is relatively simple; a short burst of 50-kHz sound waves is generated by the transducer, travels downward to the pavement surface, and is reflected back to the same transducer. The elapsed time t between sound generation and echo detection is proportional to the distance h between the transducer and the pavement surface, according to the relation

$$t = 2h/c \tag{8}$$

where c is the velocity of sound in air, approximately 1,087 ft/ sec. At the equilibrium position of the transducer, approximately 1 ft above the pavement surface, the elapsed time is about 1.8 msec. To prevent interference resulting from multiple echoes, measurements must be performed at time intervals exceeding 10 msec.

Ultrasound generation and detection are performed by electronic circuitry located within the transducer, but control and timing are performed by an interface board installed in the profilometer computer. When the computer determines that the vehicle has traveled the specified sampling distance, software commands the interface to initiate the ultrasound transmission. Later, when the echo is detected, the interface provides a count which represents the elapsed time interval (in μ sec).

The transducer's footprint—that is, the area of pavement which reflects the sound—is approximately 4 in. in diameter. Because timing stops on receipt of the earliest echo, any large object of cross section area exceeding 1 in.² or so that protrudes above the surrounding surface may be detected instead of the background surface.

Coarse surface texture can affect the measurement is two ways. First, there is inherent uncertainty in defining the distance between transducer and coarse pavements. (Which surface elevation is the right one?) Second, the uneven and randomly oriented aggregate surfaces presented by a coarse pavement may scatter the ultrasound or cause destructive interference, leading to late echo detection. This problem occurs mainly on extremely coarse (5/8 in. or greater aggregate size) chip seals. Open-graded asphalt mixes, cracks, or smaller chips do not cause difficulty. Although timing accuracy allows measurement resolution of 0.001 ft, pavement surface effects limit accuracy to 0.005 ft on smooth pavement surfaces and 0.010 ft on coarse surfaces.

During the time between signal transmission and echo detection, the vehicle traveling 55 mph moves forward approx-

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imately 1.7 in., a distance slightly greater than the transducer's diameter. No correction is made to compensate for an oblique sound path because any correction would be speed dependent and because of the impossibility of precisely identifying which areas on the transducer effectively transmitted and received the sound.

Likewise, no attempt is made to correct the distance measurement for effects of air temperature on sound velocity. The considerable variation of air temperature with height above pavement makes accurate temperature measurement over the entire sound path far more difficult than the expected measurement improvement would justify.

Because vehicle height measurements are taken at specified intervals, profile features shorter than twice that interval are inadequately sampled and are aliased into longer wavelengths. The severity of this problem depends on the short wavelength content of the profile being measured, and could only be diminished by increasing the sampling frequency or increasing the footprint of the transducer. The former alternative could be accomplished by using slower vehicle speeds or multiple transducers, but the latter is impossible without completely redesigning the transducer.

Synchronized Profile Computation

Because the times at which vehicle position u(t) and vehicle height h(x) are measured generally differ, it is necessary for the profilometer software to merge the two records and compute the profile z(x) as their difference

$$z(x) = u(t) - h(x) \tag{9}$$

That is, the software must match vehicle position measurements to height measurements taken at or near the same time.

The situation is further complicated by the delays—25 msec in the analog low-pass filter and 16 msec in the numerical integration—that are introduced into the vehicle displacement record. These delays prevent the vehicle position from being known until approximately 40 msec after the vehicle height measurement is completed.

The measurement software overcomes this difficulty by saving the vehicle height measurements, along with measurement times, in a buffer area. When vehicle displacement is computed, its time minus the known delay time is compared to the time of the oldest stored height measurement. When the times match within one-half integration period, a profile value is computed. The error introduced by the maximum time mismatch of 4 msec is negligible because of the low frequency content of the vehicle displacement record.

Profile Recording

The computed profile is stored on one of the profilometer computer's floppy disks as the profile is recorded. To conserve storage space, profile elevations at each data interval are not stored. Instead, eight-bit signed integers representing elevation differences between successive points are recorded in arbitrary units of resolution. With this scheme, a 512-kilobyte diskette may contain up to 94 mi of profile sampled at 1-ft intervals.

Filtered Profile Computation

After the profile is recorded on diskette, it may be plotted or further analyzed for roughness ratings. For both processes, is desirable to filter the profile further to remove long-wavelength components. Plotting and rating programs use a digital recursive filter with the transfer function

$$H(w) = 1/[1 + \cot^2 (\pi h/w)/\cot^2 (\pi h/w_0)]$$
(10)

This filter is a spatial low-pass filter, where w denotes the wavelength, w_0 is the desired cutoff wavelength, and h is the data interval. Its formulation, similar to that of the high-pass filter employed in the double integration, is of the form

$$p_n = Az_n + Bz_{n-1} + Cz_{n-2} + Dp_{n-1} + Ep_{n-2}$$
(11)

That is, the filtered profile p_n is computed recursively as a linear combination of the unfiltered profile z_n at the present location, the two previous unfiltered profile points z_{n-1} and z_{n-2} , and the two previous filtered profile points p_{n-1} and p_{n-2} . The coefficients A through E are computed analytically from the data interval and the cutoff wavelength.

Because the filter is recursive, the signal phase and delay become exaggerated at wavelengths near and greater than the cutoff wavelength. Figure 5 shows the transfer function of the filter at the 500-ft cutoff wavelength commonly used for profile inspection, whereas Figure 6 shows the filter's transfer function for the 50-ft cutoff wavelength used for roughness evaluation.

ANALYSIS OF ERRORS

Identification of the causes of errors cited in the draft report was essential to determine whether they were correctable or whether the potential usefulness of the profilometer was restricted by inherent shortcomings.

Profile Initialization

The first error cited in the draft report—that the beginnings of plotted profiles suffer long-wavelength distortion—was known prior to the UMTRI study, and has its cause in the filtering method used when the profile is plotted or analyzed. Because the high-pass frequency used in the integration process is very low, the recorded profile may contain a considerable amount of long-wavelength information, especially if there is significant profile slope. The high-pass filter included in the profile analysis software effectively removes these low-frequency components, but only after a distance approximately equal to the cutoff wavelength has been processed. This problem can be eliminated by recording profile data points prior to the actual beginning of the test section. Alternatively, appropriate leading data could be synthesized when the profiles are plotted, but current software has no such capability. Consequently, the





FIGURE 5 Characteristics of digital high-pass filter used to remove long-wavelength features from plotted profiles. Cutoff wavelength is 500 ft.

period during which the filtering procedure is stabilizing is characterized by a large-amplitude transient, the duration of which approximates the cutoff wavelength.

Because SDDOT has used the profilometer more as a pavement roughness measurement device then as a profile measurer, this problem has not previously been viewed as a serious error. For purposes of pavement evaluation, profiles are normally recorded in sections several miles long and filtered to remove wavelengths exceeding 50 ft. To eliminate any effect on roughness ratings, the computation software simply ignores the first 50 ft of data. When profiles are measured for plotting and inspection, testing is begun enough ahead of the area of interest to prevent transients from affecting the profile there.

Profile Underestimation

Although the problem of profile initialization was known prior to the study, profile underestimation was a completely unanticipated problem. It was apparent that the profile was either incorrectly computed or incorrectly stored, but discovery of the cause required that the entire system be checked component by component and procedure by procedure.

First, accelerometer operation was verified by inclining the unit at known angles from vertical and measuring the acceleration component from gravity. Both the primary accelerometer

FIGURE 6 Characteristics of digital high-pass filter used to remove long-wavelength features from plotted profiles. Cutoff wavelength is 50 ft.

and a spare unit were determined to have calibration errors of less than 0.5 percent over the entire range of 0 to 90 degrees of inclination. Their offsets were close to zero, and observation of their output signal showed smooth indication of both positive and negative accelerations. The gain and frequency response of the 20-Hz low-pass antialiasing filter and the accuracy of the computer's analog-to-digital converters were also verified by direct comparison of output to controlled input signals.

The mathematical derivation of the high-pass integrating filter was checked next, without discovery of any formulation errors. Computational verification of the operation was accomplished by supplying the filter with numerical sine wave acceleration signals of various frequencies and comparing the integrated displacements to analytically computed displacements.

The accuracy of the integration timing was verified by measuring the time required to execute 10^4 integration steps. Regardless of vehicle speed, disk input-output operations, or any other circumstance, the integration interval did not vary from 8.00 msec.

Finally, inspection of the software that synchronizes vehicle position and vehicle height measurements and computes the profile revealed no logic or timing errors. Instructions that checked for synchronization failure were also verified, leading to the conclusion that the profile was being accurately computed.

Although all tests indicated that the profile computations

were correct, recorded profiles showed significant errors. When the accelerometer was mounted in a manually powered test jig that moved the accelerometer in periodic motion 1.5 in. peakto-peak, and the vehicle height sensor was forced to measure a constant distance, the plotted profile amplitude was less than 1.5 in., especially at low frequencies of movement.

Inspection of the software that stores the profile on disk revealed the single problem responsible for general profile underestimation and more severe underestimation on smooth profiles and at low vehicle speeds in the UMTRI trials. As noted previously, the profile is stored as a series of integers, which, when multiplied by the unit of profile resolution, can be serially added to reconstruct the profile. The error involved truncation of this difference integer, which was computed according to the equation

$$N = G\{(z_n - z_{n-1})/R\}$$
(12)

where z_n and z_{n-1} are the current and previous computed profile elevations, R is the unit of resolution, and the function Gdenotes the greatest integer function. As a result of the truncation, a distance equal to the remainder of the division (between 0.000 and 0.005 ft) was lost from each difference representation. Had the difference equation been correctly written

$$N = G\{z_n/R\} - G\{z_{n-1}/R\}$$
(13)

the problem would not have occurred.

The fraction of profile amplitude lost by the truncation error depended on the magnitude of the profile difference. For a difference of five units of resolution (0.025 ft), the maximum error was one part in five, or 20 percent. However, for a difference smaller than one unit of resolution, the integer zero was stored, entirely eliminating the profile difference. The reason why smooth profiles and longer wavelengths were more severely underestimated was clear—in both cases, the elevation differences between succeeding data points were small, thus more drastically affected by the truncation. In the case of the UMTRI tests, the same problem caused more severe profile underestimation at lower vehicle speeds. Because the profilometer allows the data interval to be decreased at lower vehicle speeds, the medium-speed runs were conducted at 0.5-ft intervals, and the low-speed runs at 0.3-ft intervals. Because of the shorter intervals, elevation differences tended to be smaller, resulting in more significant truncation errors.

During the profilometer's early development, its operation was checked against rod and level surveys, although not with the rigor of UMTRI's analysis. Later, the present profile storage method was adopted as a means to store the data more efficiently, but rod and level checks were not repeated. Operational checks in the laboratory, using bumps mounted on moving surfaces, did not reveal the error because the bumps were blocklike, not gradual enough to be significantly affected by the truncation.

SYSTEM CORRECTIONS

The information learned from the UMTRI Road Profilometer Meeting has been used to address the two problems cited in the draft report. First, the software that records the profile has been corrected so no profile amplitude is lost in truncation. In addition, the profile resolution unit has been changed from 0.005 to 0.001 ft; this improvement in resolution has come at the small expense of decreasing the maximum elevation change to ± 0.127 ft per data interval.

Second, software will be modified to better initialize the digital filtering used to plot profiles. Because it is not always possible to record profile data ahead of the desired test section, work will concentrate on synthesizing data ahead of recorded profile data or using linear phase nonrecursive digital filters in the output programs. The latter alternative would offer the additional advantage of decreasing phase distortion at all profile wavelengths, but would also increase the profile computation time.

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PRF011: Filtered Profile Plot Program
Copyright 1986 SDDOT
Highway: 1034 From 216.00 -0.04 to 216.00 + 0.09
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FIGURE 7 Comparison of surveyed profile (lower) and profile measured by profilometer. The horizontal distance between tick marks is 100 ft; the same distance represents 4 in. vertically.

Beyond these immediate changes, procedures have been developed within SDDOT that will minimize the possibility of similar errors' occurring. Test sections of diverse profile characteristics are being surveyed by rod and level and with an E.W. Face Dipstick, an inclinometer-based surface profiler. Profilometer measurements will be compared to surveyed profiles using the same methods employed during the UMTRI study (Figure 7). Detailed results on the current performance of the profilometer will be available in the spring of 1987. Similar checks of profilometer performance will be conducted periodically to ensure continued accuracy.

OTHER IMPROVEMENTS

SDDOT has worked to improve the system's performance in areas not addressed by the UMTRI study. First, the sensitivity of the ultrasonic ranging transducer has been improved, decreasing the errors caused by coarse pavement surfaces. Negligible differences presently exist between profiles measured on coarse surfaces such as chip seals and those measured on smoothly textured pavements.

Second, two additional ultrasonic transducers have been mounted in the center of the test vehicle and at the right



 $D = (h_1 - 2h_2 + h_3)/2$

FIGURE 8 Method of rut depth measurement employed by the profilometer. Measurement approximates average of left and right wheelpath rut depths.

wheelpath, and the software has been modified to measure rut depths simultaneously with profile (Figure 8). Rut depth is measured at every other profile data point; average rut depths are recorded at specified intervals, usually 50 ft. These interval averages can be used to generate rut depth summary reports for all of the state's highway system (Figure 9).

RUT020: H 30-DEC-86	Rut Depth R 5 15:37:5	ating Da 1	ocument	Copyright 1986 SDDOT
Highway: Lane: Project:	1034 2 RUT DEPTH	ILLUSTR	ATION	Date: 04-AUG-86 Time: 11:04:10 Average Speed(mph): 53.41 Data Interval (ft): 50.00
Rut Dept1	n Analysis			
MRM 55.00	From Disp 0.000 0.100 0.200 0.300	To Disp 0.100 0.200 0.300 0.400	Average Depth 0.39 0.25 0.16 0.09	Rut Depth (inches) 0.0 0.5 1.0 * * *
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	Project	Average	0.01	·*

FIGURE 9 Sample computer output showing rut depth measurements at boundary of old rutted pavement and newer pavement. Average depth in each 0.1-mi interval is designated by an asterisk and the range of measurement by dashes.

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In addition, the profile measurement software has been modified to allow simultaneous entry of various visual highway condition ratings during profile measurement. The profilometer computer maintains a record of the entire state's rating section locations and current ratings. As the test vehicle passes through these sections, the operator is prompted to verify or update the ratings. At the end of a testing season, the updated rating file is transferred back to the department's central data base.

Finally, new profile analysis software has been developed, including programs to compute the international roughness index and perform power spectrum analysis of the recorded profiles.

On the basis of the profilometer's performance following the corrections and recent improvements, SDDOT has decided to supply specifications, descriptions, and schematic diagrams to other state transportation departments. To date, two other states have decided to build similar instruments at an anticipated cost, excluding vehicles, of \$20,000 each.

CONCLUSIONS

It is unfortunate that the profile underestimation error existed in the SDDOT profilometer during the UMTRI tests, because it completely precluded the possibility of determining the system's potential performance and prevented discovery of less significant errors. On the positive side, discovery of the error has enabled SDDOT to correct the problem and to verify that no other serious errors exist.

Above all, the experience has demonstrated the importance of independent verification of profilometer operation. Recent validation tests indicate that the corrected system provides valid and reliable profile and rut depth measurements. SDDOT will continue to test and improve its profilometer to achieve the highest possible performance consistent with its low cost.

REFERENCES

- 1. M. W. Sayers and T. D. Gillespie. *The Ann Arbor Road Profilome*ter Meeting Draft Report. University of Michigan, Transportation Research Institute, Ann Arbor, 1985.
- D. L. Huft. The South Dakota Profilometer. In *Transportation Research Record 1000*, TRB, National Research Council, Washington, D.C., 1984, pp. 1–8.

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