South Dakota Profilometer

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ABSTRACT

In order to provide accurate and consistent pavement roughness measurements for its pavement management system, the South Dakota Department of Transportation designed and constructed a profilometer system during the fall and winter of 1981-1982. A linear accelerometer and a noncontact ultrasonic ranging device mounted on a standard automobile and controlled by an onboard microcomputer measure a vehicle's independent profile at normal urban and rural highway speeds. In approximately 10 weeks of operation during the summer of 1982, more than 8,000 lane-miles of highway were tested; because of the high degree of automation in processing the measurements, the entire state highway system's roughness ratings were computed and entered into the Department's central highway data base within 3 weeks following completion of field measurements. The roughness measurements are a major input component in the analysis the Department uses to assign priorities and program construction projects.

Because pavement roughness has long been recognized as one of the most significant indicators of overall pavement condition and performance, most states have established roughness measurement programs. A variety of systems have been devised to perform the measurements, but most currently used are response-type road roughness measurement systems that measure the severity of a test vehicle's response to the profile of the roadway being tested. Although such systems have some usefulness, they generally suffer one serious drawback: because the responses of different test vehicles (and even of the same vehicle at different times) vary widely, it is difficult to establish and maintain calibration. In addition, the roughness ratings, usually in inches per mile, are often difficult to relate to pavement properties. Before 1981 the South Dakota Department of Transportation used a response-type system.

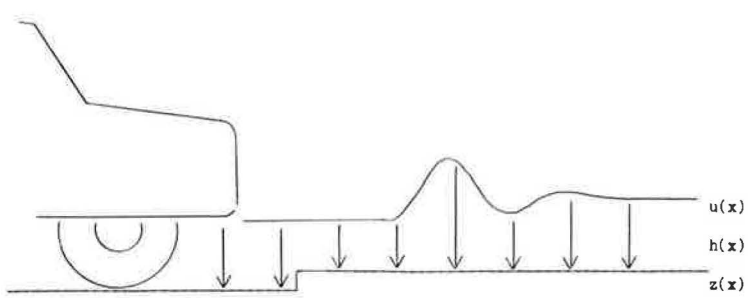
A second group of roughness measuring systems includes those devices that are designed to measure the actual roadway profile instead of a vehicle's response to the profile. Both low- and high-speed profilometers have been designed. Because the measurements obtained from these systems are essentially independent of the test vehicle suspension characteristics, calibration is more easily established and maintained. During the fall and winter of 1981-1982, the South Dakota Department of Transportation (SDDOT) designed, constructed, and tested a high-speed, noncontact profilometer that was used to test the entire state highway system during the summer of 1982. The profilometer and the current use of profile measurements are described in this paper.

PRINCIPLE OF OPERATION

In order to understand the principles involved in high-speed profilometery, it is useful to consider a vehicle's response to a step in a roadway profile (Figure 1). In this discussion, the lower front corner of the vehicle body is chosen as the vehicle's point of reference.

Before encountering the profile step, the vehicle body maintains an equilibrium position at some distance above the roadway surface. When the wheel encounters the step, the wheel and then the vehicle body are driven upward. Depending on the characteristics of the vehicle suspension, the body assumes a damped periodic motion, until it again attains its equilibrium position. The record of the vehicle's vertical position is described by the curve u(x), where x is the roadway distance coordinate.

The vehicle height above pavement h(x), the distance between the vehicle reference point and the roadway surface, depends on both the profile and the vehicle motion. Before encountering the step, the height is the equilibrium distance; from the time the reference point is above the step until the vehicle's periodic motion is completely damped, the height varies, dependent on both the height of the profile step and the vehicle's response. Finally, the equilibrium height is again attained.



$$z(x) = u(x) - h(x)$$

FIGURE 1 Profile measurement principle.

It is apparent that the vehicle height above pavement at any position x is given as the difference between the vehicle's position u(x) and the roadway profile z(x). That is:

$$h(x) = u(x) - z(x) \quad (1)$$

It can be concluded that if both u(x) and h(x) can be measured, then the profile z(x) may be computed as

$$z(x) = u(x) - h(x) \quad (2)$$

Most important, although both measurements u(x) and h(x) depend on the vehicle's response, their difference z(x) representing the roadway profile does not. Indeed, for any vehicle response motion u(x), a corresponding vehicle height h(x) is measured such that their difference corresponds to the roadway profile z(x). In summary, if vehicle position u(x) and vehicle height above pavement h(x) can be measured, the profile z(x) can be computed.

INSTRUMENTATION

The profilometer consists of a standard full-size automobile equipped with a microcomputer and associated electronic instrumentation to measure and record a single profile.

A Digital Equipment Corporation LSI-11/23 microcomputer riding on the back seat of the test vehicle forms the basis of the profilometer instrumentation system. Executing profile measurement software written by the SDDOT, the computer controls the devices that measure the vehicle's horizontal distance, vertical position, and height above pavement, then computes and records the highway profile in real time as the vehicle moves at normal traffic speeds.

The microcomputer is equipped with flexible diskette (floppy disk) drives for storage of operating programs and profile data, a handheld typewriter-style keyboard-display terminal for operator interaction, and a line printer. A 500-watt sine wave inverter located in the trunk of the vehicle provides 115 V AC power to the entire system.

VEHICLE DISTANCE MEASUREMENT

To make the measured profile distance-based, that is, to record profile elevations at equally spaced intervals, the microcomputer is equipped with a horizontal distance-measuring interface. The device, constructed on a single wirewrap prototype development board and installed directly in the computer's backplane, has the capability to accept a desired measurement interval distance under software control. By counting electrical pulses generated by a magnetic pickup that senses magnets attached to the vehicle's left front wheel, the device accurately measures distance and informs the microcomputer each time the vehicle moves the specified distance. For normal roughness survey purposes, the device is programmed to detect 1-ft intervals; for special purposes, any other interval may be selected.

VEHICLE POSITION MEASUREMENT

The vertical position u(x) of the vehicle reference point is determined by using a linear accelerometer, the voltage output of which is proportional to the vertical acceleration of the vehicle body (Figure 2). The acceleration signal is filtered by an analog lowpass filter to remove high frequency (greater than 25 Hz) components corresponding to spurious

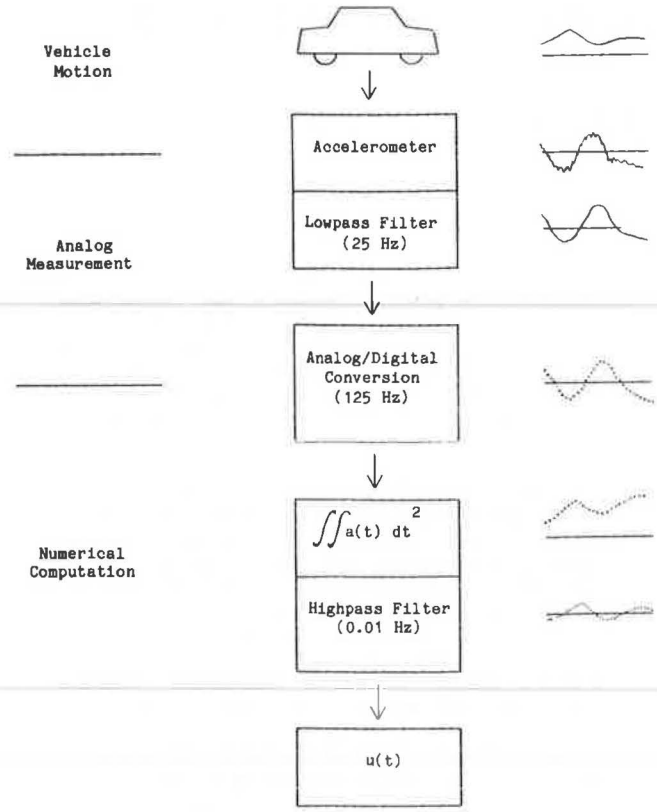


FIGURE 2 Measurement of vehicle position.

vehicle body vibrations, then sampled by the microcomputer's analog-to-digital converter at a programmable clock-controlled rate of 125 Hz. Because acceleration is inherently temporal, the vehicle position record is computed as a function of time rather than distance, as the double integral of acceleration with respect to time:

$$u(t) = \int\int a(t)\, dt^2 \quad (3)$$

Two considerations dictate that this integration be modified by highpass filtering to remove extremely low frequency acceleration components that correspond to long wavelength profile features such as hills and valleys. First, offsets induced by accelerometer tilt and electronic drift also appear as low frequency, nearly constant terms in a(t); these would generate errors in u(t) proportional to the square of time, quickly overwhelming the true long-term profile. Furthermore, even if offset errors were not present, true profile measurement would be possible only if the vehicle's initial conditions--elevation and vertical velocity--were precisely known. Such instrumentation would increase system cost by at least one order of magnitude. By removing signal components corresponding to both offset errors and true long wavelength profile features, highpass filtering forces the computed vehicle position u(t) to remain numerically close to zero, in effect making the long-term vehicle position record an assumed horizontal line.

After the acceleration is digitized, a single numeric operation simultaneously performs both the double integration and highpass filtering. The nominal 3 db cut-off frequency of 0.01 Hz corresponds to a wavelength of approximately 8,000 ft at 55 miles per hour. Because longer wavelength features such as hills, valleys, and long inclines are

essentially removed from the vehicle position record, they are missing from the computed surface profile as well. For computation of roughness ratings, these features are not important anyway; it must be remembered that the measured profile does not represent an accurate long distance survey, however.

VEHICLE HEIGHT MEASUREMENT

The record of vehicle height above pavement is measured by an ultrasonic ranging device mounted directly beneath the linear accelerometer (Figure 3). The transducer transmits a 150-microsecond pulse of 50 KHz sound waves downward to the pavement surface, which reflects the sound to the same transducer.

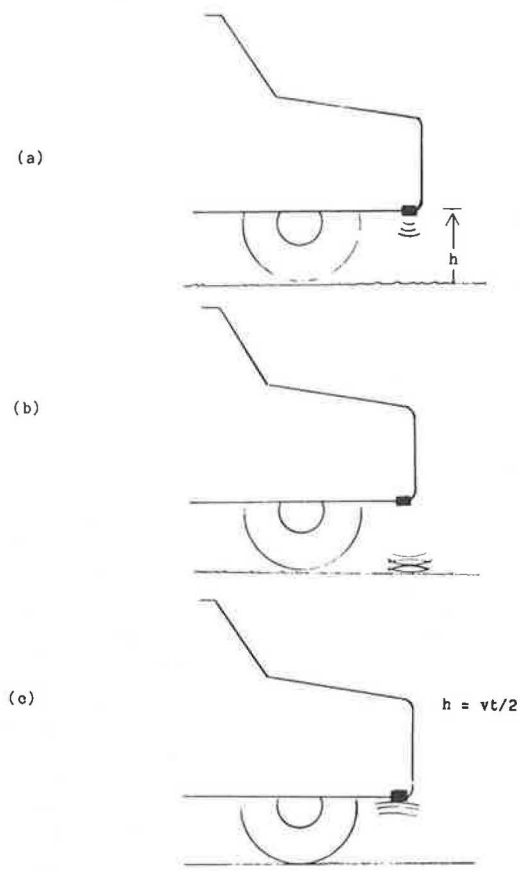


FIGURE 3 Measurement of vehicle height.

The elapsed time between transmission and detection of the reflected echo is proportional to the vehicle height, according to the relation:

$$h = vt/2 \qquad (4)$$

where v is the velocity of sound in air, approximately 1,090 ft per second.

Ultrasound transmission and echo detection are controlled by a custom interface constructed on a single wirewrap prototype board installed in the microcomputer's electrical bus. The interface is capable of initiating a height measurement under software control, generating a program interrupt when the measurement is complete, and providing a count representing the elapsed time. Although the count is recorded in microseconds, allowing very fine measurement resolution, the accuracy of the ultrasonic ranging device is limited by the ability to cleanly detect the 50 KHz echo. On sound pavement surfaces, variations in the surface macrostructure can induce echo phase shifts, leading to an uncertainty of one half-period (10 microseconds) in the time measurement, corresponding to a distance uncertainty of 0.005 ft.

Extremely irregular surfaces may scatter the ultrasound so severely that the echo is detected either very late or not at all. Although this problem occurs less than one measurement in one thousand on most asphalt and concrete pavements, it is troublesome on coarse chip sealed pavements. Work is in progress to improve operation on this surface type. Meanwhile, the profile measurement software detects and counts poorly received echos, and flags each affected profile measurement. Subsequent software may then replace these measurements with interpolated values, if desired.

The ultrasonic transducer is an instrument grade version of the transducer used by Polaroid on autofocusing cameras, mounted in 1.5-in. Polyvinyl chloride pipe fittings. It withstands temperature extremes and dust, and is insensitive to wheel, engine, and other traffic noises. It is not waterproof, however, and although the unit will work in conditions of light mist, operation must be suspended during rain showers.

PROFILE DETERMINATION

Because vehicle position is computed at equal intervals of time while vehicle height above pavement is computed at intervals of distance equal to the desired profile data interval, the two records must be merged by software methods. At the conclusion of each vehicle height measurement, the height is subtracted from the most recently computed vehicle position, giving the profile value at that point. The difference between that value and the previous profile value is then stored on diskette. Comparison of successively measured profiles of the same highway section reveals the measurement repeatability over both short (Figure 4) and long distances (Figure 5). Although it is somewhat difficult to ensure identical vehicle paths for repeated test runs, the repeatability of both plotted profiles and computed roughness ratings has been very good.

OPERATION

Because system efficiency and ease of use are important considerations, the profilometer instrumentation and controlling software are designed to maximize machine work and minimize operator effort. There are no calibrations or field adjustments to be made, and the computer is "friendly"--the operator is prompted whenever input is required. Simplified operational procedures enable a two-man crew to achieve a consistently high level of production.

Preparation

The crew, consisting of driver and operator, is responsible for planning test routes so the greatest number of lane-miles are tested for the number of miles driven. In rural test areas, a daily route of approximately 350 to 400 miles is planned; of these, an average of 200 miles are tested. (This is largely the result of having a limited number of access

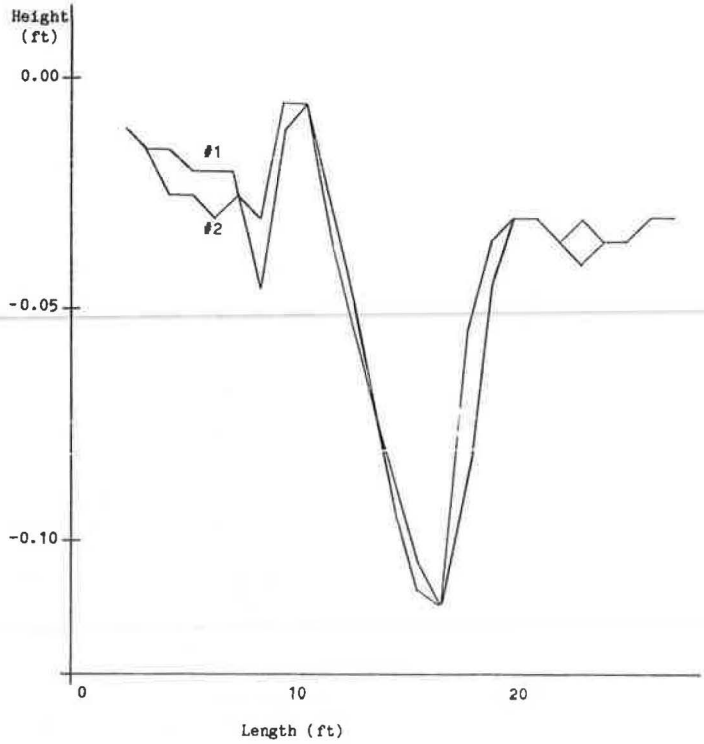


FIGURE 4 Short distance profile repeatability.

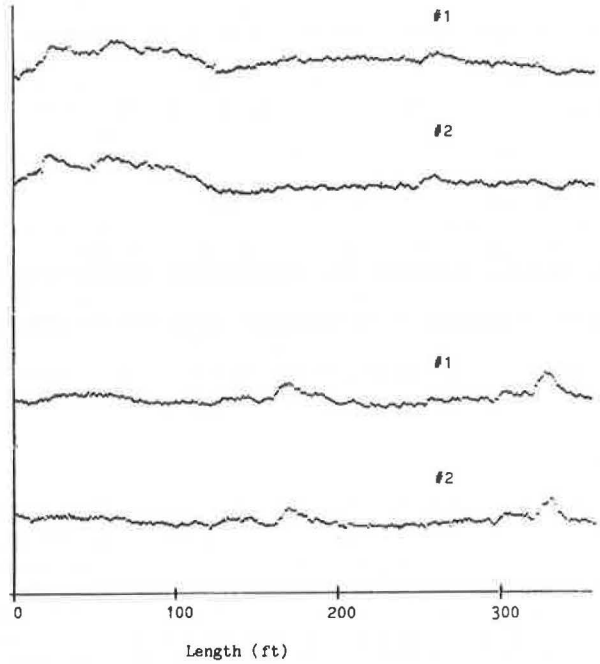


FIGURE 5 Long distance profile repeatability.

routes from the central office to the state perimeter areas.) Before beginning a 4-day workweek, the entire week's route is mapped and overnight layover locations are determined.

The crew is also responsible for routine system maintenance, including verifying the equipment's operation using quickly executed diagnostic programs at daily intervals, checking the appearance of exposed instrumentation and wiring, and ensuring that adequate supplies of computer paper and diskettes exist.

Test Procedure

Before beginning profile measurement, the operator must identify the highway to be tested and verify that sufficient disk storage exists to record the intended test length. After being informed that the system is ready to begin profile measurement, the driver initiates car motion. At the beginning point, the operator enters the begin command, optionally specifying the mileage reference marker (MRM) of that point. As subsequent MRMs are encountered, the operator enters their identification, continuing until the end of the project is reached.

After the entire profile is measured, the operator identifies the project location and may enter remarks concerning pavement condition, weather, or any other pertinent information. The existence and order of MRMs are verified against the computer's master MRM file, and the operator is given opportunity to correct errors. Figure 6 shows the operator action required on a short test project.

OUTPUTS

When roadway profiles are measured, they are recorded on magnetic media and documentation of test activity is printed. Although the profiles may be further analyzed in the field, plotting and roughness rating computations are normally performed later in the laboratory.

Raw Profile Data Files

The measured profile and associated information for each project are placed on a flexible diskette in a

```
PRF001:  SDDOT Profilometer System

Operators?  OVERBAY & SCHAACK

Highway  1014 W                                   (Identify highway)

72.5 miles remain on disk 110                    (Verify that sufficient
Change disk?  NO                                   space exists on disk)

PRF001 ready--

*B                                              (Begin recording profile)
*M233                                            (Locate Mileage Reference
*M235                                          Markers as they are passed)
*M231
*E                                                        (End profile)

Lane?  2                                         (Identify lane number)

Project?  EAST OF PIERRE                            (Identify location)
Remarks?  EXAMPLE                               (Miscellaneous remarks)

MRM changes/deletions?                          (Correct MRM error above)
From?  235
  To?  232

Highway?                                       (Next highway, if desired)

PRF001 done
```

FIGURE 6 Typical operator input.

file named after the project's highway and approximate MRM. Each diskette contains up to 94 miles of profile data, assuming a data spacing of 1 foot. All further analysis is based on the information contained in these files.

Field Activity Reports

For each test project, a record of field test activity is printed on the line printer (Figure 7). The highway, lane, and project identification as well as the date and time of test are indicated first; other parameters relating to the test conditions follow. These include identification of the test vehicle and specification of the average test speed, data interval, vertical resolution of the recorded profile, total number of data points, and number of data points at which no valid ultrasonic echo was received.

A list of project location events follows, including the location of the test beginning and ending and the occurrence of mileage reference markers throughout the project. For sections between MRMs, the ratio of distance measured by the profilometer system to the distance recorded in the MRM inventory is computed and printed; deviations exceeding 5 percent are flagged, providing a check on the system's distance measurement and enabling seriously misplaced MRMs to be detected.

Normally, field activity reports are sorted and filed in order of highway and MRM. The identification of the disk number and project file name then enable the project profile to be easily referenced for further analysis.

Profile Plots

Measured profiles may be plotted on the system's line printer (Figure 8). Each profile data point is

```
PRF001:  Profilometer Field Activity Document

Highway: 1014 W
Lane:    2
Project: EAST OF PIERRE
Remarks: EXAMPLE
   Date:  16-NOV-83
   Time:  15:13:26

       Test Vehicle:  000476
Average Speed (mph):  49.383
 Data Interval (ft):   1.000
    Resolution (ft):   0.005
   # of Data Points:   18100
  # of Bad U/S Data:       1

Project                              Distance
 Event        MRM       Disp          Ratio

 Begin      233.00     0.864
            223.00
            232.00                     1.001
            231.00                     0.997
End         231.00     0.574

Disk:    110
File:  0140W0.233
Operators:  OVERBAY & SCHAACK
```

FIGURE 7 Profilometer field activity document.

```
PRF010: Profile Plot
25-NOV-83 20:50:58

Highway: 1014 W
   Lane: 2
Project: EAST OF PIERRE
Remarks: EXAMPLE
   Date: 16-NOV-83
   Time: 15:13:26

       Test Vehicle: 000476
Average Speed(mph): 49.383
 Data Interval(ft):  1.000
    Resolution(ft):  0.005
  # of Data Points:  18100
 # of Bad U/S Data:      1

Filtered Profile Plot
Highpass wavelength: 500.00
(Profile 1/4 actual scale)

231.00
```

FIGURE 8 Profile plot.

represented by a single dot; tic marks indicate each interval of 50 data points. The plotting software includes highpass filtering to eliminate long wavelength features if desired. Those profile features of wavelength longer than the specified cutoff wavelength are attenuated, while those of shorter wavelength are unaffected (Figure 9).

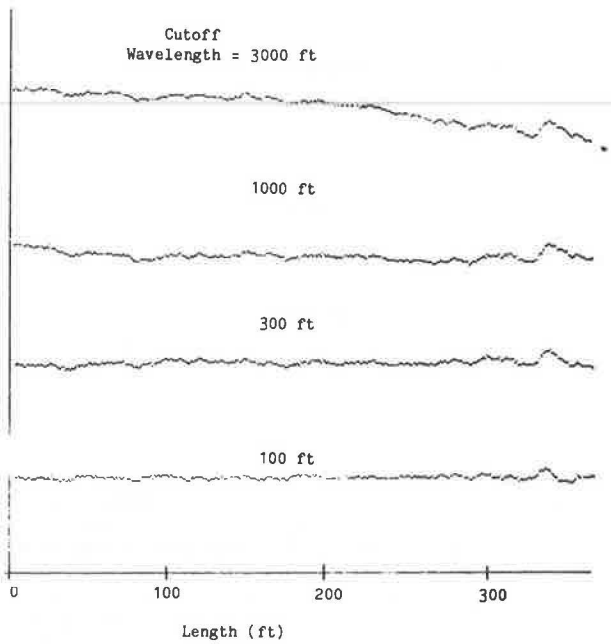


FIGURE 9 Profile filtering.

Although profile plots are useful for verification of system operation and for detailed analysis of specified highways, they are not routinely generated for roughness surveys. Visual inspection of several thousand miles of profile is simply not practical.

Roughness Ratings

Roughness ratings are computed as a function of the mean square power present in the measured profile at wavelengths shorter than 50 ft (Figure 10). The profile is first filtered to remove longer wavelength components, then the power is computed as

$$P = (1/L) \int^2 z(x)\, dx \tag{5}$$

where L is the length of the section being considered. Finally, a roughness rating between zero and five is computed as

$$5 \exp \left\{ -[\ln(P) + 13.42/4.38]^3 \right\} \tag{6}$$

This formula, derived through comparison of power P to a panel's subjective roughness ratings for a diverse sampling of pavement surfaces, assigns a roughness rating of five for extremely smooth pavements, whereas ratings lower than one are given to the roughest pavements on the state highway system. Figures 11 and 12 show roughness ratings for a highway section composed of two distinct pavement types; although most of the roadway is an older asphalt pavement, the last three quarters of a mile are 2-year-old concrete pavement. Comparison of the two figures reveals the degree of repeatability in the ratings.

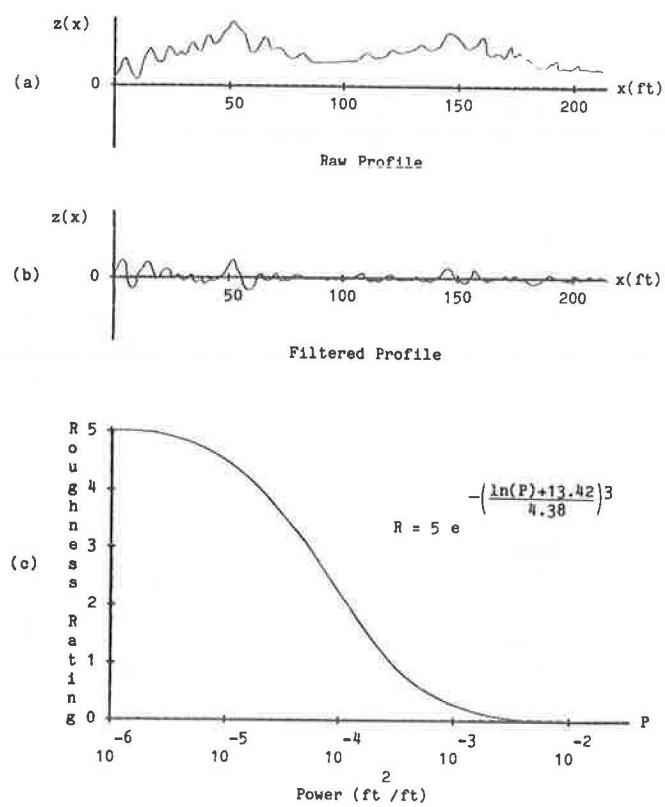


FIGURE 10 Roughness computation.

```
PRF020:  Roughness Rating Document
25-NOV-83 20:50:58

Highway:  1014 W
   Lane:  2
Project:  EAST OF PIERRE
Remarks:  EXAMPLE
   Date:  16-NOV-83
   Time:  15:13:26

       Test Vehicle:  000476
Average Speed (mph):  49.383
 Data Interval (Ft):   1.000
   Resolution (Ft.):   0.005
   # of Data Points:   18100
  # of Bad U/S Data:       1

Roughness Analysis

          From      To      Rough-      Very
 MRM      Disp      Disp     ness     5 Good  4 Good  3 Fair  2

231.00  -0.574   -0.287    2.22     ************************
        -0.287    0.000    2.95     ******************
231.00   0.000    0.250    2.46     **********************
         0.250    0.500    3.10     *****************
         0.500    0.750    3.05     ******************
         0.750    1.000    4.14     ********
232.00   0.000    0.250    3.73     ***********
         0.250    0.500    2.96     ******************
         0.500    0.750    4.02     *********
         0.750    1.000    3.29     **************
233.00   0.000    0.288    4.94     *
         0.288    0.576    4.22     *******
         0.576    0.864    3.90     *********

Project Average            3.29     **************

Disk: 110
File: 0140W0.233
Operators:  OVERBAY & SCHAACK
```

FIGURE 11 Roughness rating document.

```
PRF020:  Roughness Rating Document
25-NOV-83 21:12:06

Highway:  1014 W
   Lane:  2
Project:  EAST OF PIERRE
Remarks:  EXAMPLE
   Date:  16-NOV-83
   Time:  16:08:50

       Test Vehicle:  000476
Average Speed (mph):  49.972
 Data Interval (Ft):   1.000
   Resolution (Ft.):   0.005
   # of Data Points:   17974
  # of Bad U/S Data:       0

Roughness Analysis

          From      To      Rough-      Very
 MRM      Disp      Disp     ness     5 Good  4 Good  3 Fair  2

231.00  -0.569   -0.284    2.28     ************************
        -0.284    0.000    2.93     ******************
231.00   0.000    0.250    2.55     **********************
         0.250    0.500    3.13     *****************
         0.500    0.750    3.08     ******************
         0.750    1.000    4.10     ********
232.00   0.000    0.250    3.80     ***********
         0.250    0.500    3.02     ******************
         0.500    0.750    3.89     **********
         0.750    1.000    3.19     ***************
233.00   0.000    0.282    4.94     *
         0.282    0.563    4.40     ******
         0.563    0.845    4.24     *******

Project Average            3.33     **************

Disk: 110
File: 0140W0.232
Operators:  OVERBAY & SCHAACK
```

FIGURE 12 Roughness rating document.

PAVEMENT MANAGEMENT SYSTEM INPUT DATA

The primary use of the profilometer system is to supply the SDDOT's construction priority assignment analysis with pavement roughness measurements. The computerized analysis determines the sufficiency of the current pavement, estimates the year of construction need, and arranges proposed construction projects in order of priority; the priorities so determined may be overruled only with strong justification. Because roughness measurements constitute one of the primary components involved in the analysis (others include visually determined surface condition, in-place pavement thickness and design, roadway strength, current maintenance cost, and traffic load), timely, accurate, historically consistent measurements are mandatory. The present schedule calls for annual testing of the entire state highway system.

For every project tested, single-lane roughness ratings are computed over approximate quarter-mile sections and recorded on a floppy disk in a format acceptable for input to the central mainframe computer. Because no manual data coding is required, the ratings are quickly available. In 1982 approximately 8,000 lane-miles of roughness ratings were computed and entered into the central roadway data base within a period of 3 weeks following completion of field testing.

COSTS

An important requirement of a profilometer system is that its acquisition, operation, and maintenance costs be low.

Acquisition Cost

Although development costs of the profilometer have been substantial, the actual cost of duplicating the present system is reasonable. The hardware and installation costs may be summarized:

Hardware	Cost ($)
Microcomputer system	9,000
Handheld alphanumeric terminal	500
Line printer	600
Linear accelerometer	1,000
Acceleration lowpass filter*	100
Analog-to-digital converter	800
Programmable clock	600
Ultrasonic ranging transducer/interface*	400
Vehicle distance interface*	400
500-watt, 12-V DC to 115-V AC inverter	1,500
Hardware, connectors, wiring	500
Total	15,400

The items followed by an asterisk are not commercially available, and require construction. For these items, only the cost of materials (components, foundation boards, enclosures, etc.) is shown. Although labor costs for assembly and system installation are not included, a total cost estimate of $20,000 appears adequate.

Operation Cost

Based on 1982 experience, the average cost of measuring and recording highway profiles in a program of statewide testing can be estimated as follows:

	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-