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Description and Evaluation of the South Dakota Road Profiler

Demonstration Project No.72 Automated Pavement Data Collection Equipment

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November 1989

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16. Abstract

This project was conducted to describe and evaluate the South Dakota Road Profiler for Demonstration Project 72, "Evaluation of Equipment for Measuring Pavement Roughness and Rut Depth".

The Road Profiler's profile and rut depth performance were evaluated by comparisons to surveys taken with rod and level and the E.W. Face "Dipstick". For each of ten sites, the Road Profiler's measurements at 25, 40 and 55 miles per hour were compared to the manual surveys. Spectral analysis and the International Roughness Index were used to compare profile data, while plots and averages were used to compare rut depth data.

The Road Profiler's profile and rut depth measurements correlated well with Dipstick measurements. Minor sensitivity to pavement texture was observed. No operational difficulties were encountered.

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Description and Evaluation of the South Dakota Road Profiler

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November 1989

METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
in	inches	2.54	millimetres	mm
ft	feet	0.3048	metres	m
yd	yards	0.914	metres	m
mi	miles	1.61	kilometres	km
	AREA			
in^2	square inches	645.2	millimetres squared	mm^2
ft^2	square feet	0.0929	metres squared	m^2
yd^2	square yards	0.836	metres squared	m^2
mi^2	square miles	2.59	kilometres squared	km^2
ac	acres	0.395	hectares	ha
	MASS (weight)			
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
	VOLUME			
fl oz	fluid ounces	29.57	millilitres	mL
gal	gallons	3.785	litres	L
ft^3	cubic feet	0.0328	metres cubed	m^3
yd^3	cubic yards	0.0765	metres cubed	m^3

NOTE: Volumes greater than 1000 L shall be shown in m^3.

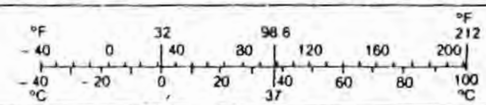
	TEMPERATURE (exact)			
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

* SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
	LENGTH			
mm	millimetres	0.039	inches	in
m	metres	3.28	feet	ft
m	metres	1.09	yards	yd
km	kilometres	0.621	miles	mi
	AREA			
mm^2	millimetres squared	0.0016	square inches	in^2
m^2	metres squared	10.764	square feet	ft^2
km^2	kilometres squared	0.39	square miles	mi^2
ha	hectores (10 000 m^2)	2.53	acres	ac
	MASS (weight)			
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1 000 kg)	1.103	short tons	T
	VOLUME			
mL	millilitres	0.034	fluid ounces	fl oz
L	litres	0.264	gallons	gal
m^3	metres cubed	35.315	cubic feet	ft^3
m^3	metres cubed	1.308	cubic yards	yd^3

	TEMPERATURE (exact)			
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



These factors conform to the requirement of FHWA Order 5190.1A.

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ABBREVIATIONS

DEC	Digital Equipment Corporation
FHWA	Federal Highway Administration
ft	feet
g	32.2 feet per second^2
Hz	Hertz (cycles per second)
IRI	International Roughness Index
km	kilometer
m	meter
mm	millimeter
mph	miles per hour
MRM	Mileage Reference Marker
pi	pi=3.14159 approximately
PSI	Present Serviceability Index
SDDOT	South Dakota Department of Transportation
sec	second
vac	volts alternating current
vdc	volts direct current

5. All measurements should be referenced to the state highway system at the time of collection.

This combination of goals has resulted in the development of a system which measures profile and rut depth with medium accuracy. Like expensive "profilometers", the Road Profiler is an inertial instrument which measures profile independently of test vehicle dynamics. Unlike more expensive equipment, it uses ultrasonic ranging devices rather than optical sensors to measure both profile and rut depth, reducing system costs by tens of thousands of dollars.

Where possible, commercially available components are used. When necessary, mechanical and electronic components have been designed and constructed by SDDOT's instrumentation group and machine shop. This construction is within the capability of most state transportation departments.

The Road Profiler is simple to operate. Few operator adjustments are required, and the profile measurement software is easy to use. Average production rates of seven hundred lane miles per forty-hour week are consistently attained.

Finally, the Road Profiler's computer contains the state's entire highway and reference marker inventory system, so every measurement is immediately assigned a valid location. All analysis software generates information consistent with the referencing system.

2.2 Test Vehicle

The current version of the Road Profiler is mounted in a 1986 Ford van (Figure 2). The system is compact enough to be mounted in a passenger car, but a van is better suited to mounting the sensors required to measure rut depth. A van also provides more operator comfort and better access to the equipment.

The vehicle is equipped with an engine large enough to maintain vehicle speed, run the vehicle's air conditioner and power a 105 amp high capacity alternator. The alternator provides sufficient 12vdc capacity to power a 500 watt, 115vac sinewave inverter (Figure 3) which in turn powers the various electronic instrumentation. This method of ac power generation was chosen because it is more compact, quieter, and more dependable than an auxiliary generator. Furthermore, the inverter requires no routine maintenance and has a much longer life expectancy. It can be controlled

Figure 2: South Dakota Road Profiler

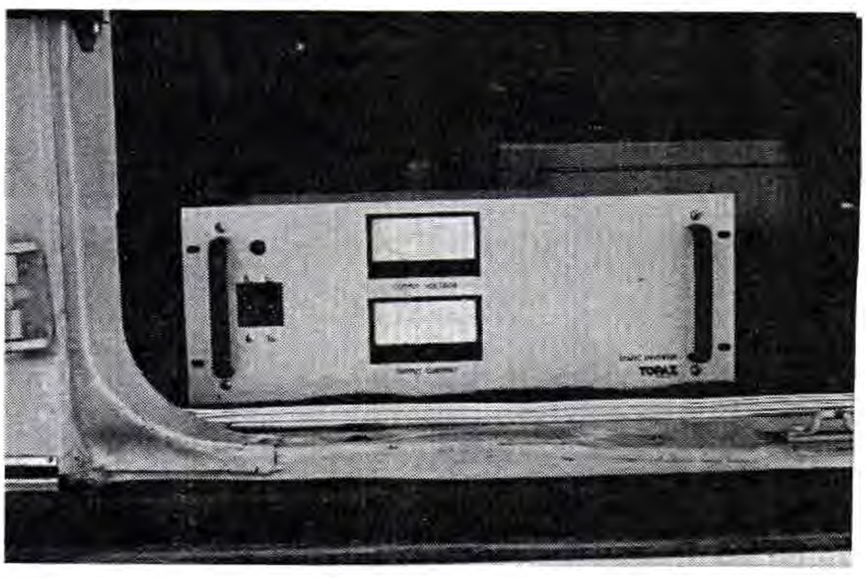


Figure 3: 500 Watt Sinewave Inverter

remotely by a switch mounted beneath the vehicle's dash and is equipped with an alarm which sounds if the inverter is left on after the vehicle is shut off.

The vehicle's front bumper has been replaced by a 9x4x81" aluminum channel which houses the Road Profiler's external sensors. The channel attaches to the vehicle's frame yokes, and is strong enough to protect the sensors from minor collisions but light enough to maintain the vehicle's weight distribution. It is machined to permit convenient sensor removal.

Although most of the states which have duplicated the Road Profiler have also used full size vans, one (Wyoming) used a mini-van very successfully. Another (Wisconsin) is using a sedan until a van can be purchased.

2.3 Road Profiler Computer

The foundation of the Road Profiler's electronic instrumentation is a microcomputer of the Digital Equipment Corporation (DEC) PDP11/73 family (Figure 4). The computer is equipped with a sixteen bit processor, 256 kilobytes of memory, dual eight inch floppy disks, and a twenty megabyte ruggedized hard disk. It utilizes RT-11, a standard DEC operating system designed for real-time data acquisition applications.

The computer is configured to perform the physical measurements necessary to determine roadway profile and rut depth. Two commercially available interfaces--a programmable clock and an analog-to-digital converter--provide timekeeping and voltage measurement capability. In addition, the computer contains three interfaces designed by SDDOT and constructed from breadboard modules compatible with the computer's backplane. The first connects to a transmission pulse sensor and allows the computer to measure the distance traveled by the vehicle. Another operates the three ultrasonic ranging sensors which measure distances between vehicle and pavement. The third provides power and signal conditioning for the accelerometer used to measure vehicle motion.

The accelerometer and transmission pulse sensor are commercially available items. The ultrasonic ranging sensors must be constructed from wirewrap foundation boards and various electronic components, however. The sensor circuit was designed by SDDOT.

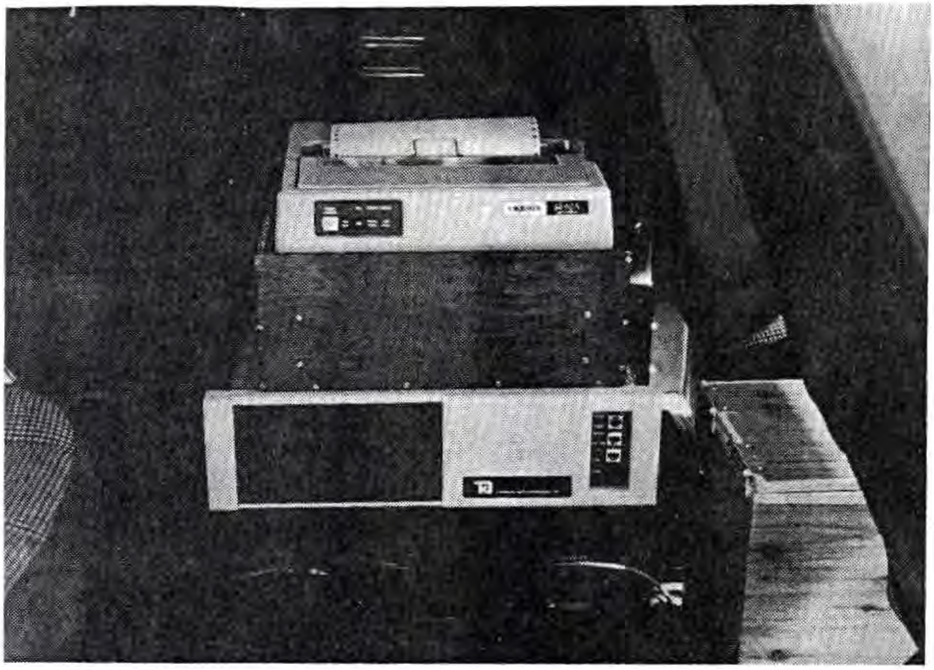


Figure 4: Road Profiler Computer and Printer

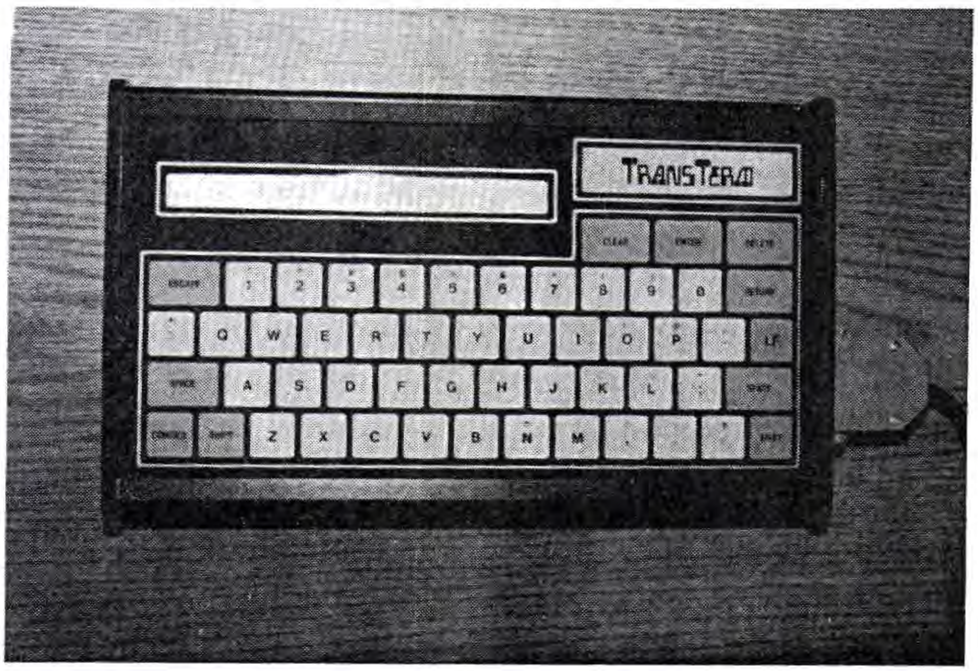


Figure 5: Handheld Computer Terminal

While the accelerometer and transmission pulse sensor are commercially available items, the ultrasonic ranging sensors are designed and constructed by SDDOT. Like the SDDOT computer interfaces, they are assembled from readily available components using wire wrap techniques on breadboard modules.

A small handheld terminal with a membrane keyboard and liquid crystal display (Figure 5) allows the operator to enter commands and to identify highways, locations and descriptions. The terminal, which is powered by the computer's twelve volt supply, displays two lines of forty characters each. While a two-line display is unacceptable for general data processing work, it accomodates the profile measurement software which was written to match this terminal well. The terminal is small enough to be held on the operator's lap.

An inexpensive dot matrix printer prints one-page test summaries immediately after testing. It can also generate most of the data analysis documents, including profile and rut depth plots. Plots, although somewhat slow and of moderate quality, can be produced in the field for immediate review.

2.4 Highway Reference

Profile and rut depth measurements are immediately referenced to the state's highway and reference marker system. The Road Profiler computer contains a Highway/MRM Inventory of all legal highway numbers, the identity of all Mileage Reference Markers (MRMs), and the True Mileage of each MRM from the highway's origin. As the operator identifies each MRM passed by the test vehicle, the measurement software verifies its identity and flags its location in the profile and rut depth data.

The Road Profiler measures distances between and beyond MRMs by counting pulses generated by the transmission sensor. The measured distance between MRMs is compared to the computer's inventory of True Mileage, and significant deviations are flagged on the printed test report. In this manner, mileage errors in the Highway/MRM Inventory can be corrected.

2.5 Profile Measurement

Like several other road profile measurement systems, the Road Profiler is an "inertial" device. That is, it measures profile relative to a reference plane inferred from measurements of the vehicle's vertical motion. Specifically, the roadway profile is computed as the difference between the vehicle's position in space and the distance between the vehicle and the pavement surface.

Vehicle motions are sensed by a linear servo accelerometer mounted on the aluminum beam which replaces the vehicle's front bumper. The accelerometer generates an electrical signal proportional to the vehicle's vertical acceleration. This signal is filtered to remove frequencies higher than 20Hz which correspond to extraneous vibrations, then digitized 125 times per second and integrated numerically to produce a record of vehicle position as a function of time. The integration algorithm incorporates digital filtering to remove extremely low frequencies (less than 0.01Hz) which contain errors arising from accelerometer tilt and electronic offsets.

The distance between the accelerometer and the pavement surface is measured by an ultrasonic ranging device. A transducer similar to those found on Polaroid autofocusing cameras transmits a short burst of 50KHz sound toward the pavement surface. After the sound is reflected upward by the pavement, it is detected by the same transducer. The distance between the transducer and the pavement surface is computed from the elapsed time between sound generation and echo detection.

Each ranging measurement is subtracted from the current vehicle position to produce the computed roadway profile. The frequency of profile computation is limited by the maximum measurement rate of the ultrasonic transducer, approximately one hundred samples per second. Usually, profiles are measured at one foot intervals at speeds up to sixty miles per hour, but shorter intervals are possible at lower vehicle speeds.

Profiles are measured in the left wheelpath, but right wheelpath operation could be accomplished by repositioning the accelerometer and ultrasonic transducer. Software changes and a second accelerometer would be required to measure both profiles.

Measured profiles are stored on floppy disk for later analysis. Profiles may be plotted or used to compute roughness ratings, including the International Roughness Index.

2.6 Rut Depth Measurement

Rut depths are estimated using the profile measurement ultrasonic ranging device located at the left wheelpath and identical sensors mounted at the center of the vehicle and at the right wheelpath. Rut depth D is computed as

$$D = (h_1 - 2h_2 + h_3)/2 \qquad (1)$$

where h_1, h_2 and h_3 are the respective distances between the pavement and the left, center, and right sensors. This quantity represents the height of the hump between the wheelpaths, and approximates the average of left and right wheel path rut depths. The three sensor system was chosen because of its simplicity and to avoid problems which result from an overwidth vehicle with sensors mounted outside the wheelpaths. This arrangement demands that the test vehicle's driver maintain an accurate course in the wheelpaths.

Rut depth is measured at every other profile measurement point, so the normal measurement interval is two feet. It is not necessary to record every rut depth measurement, however. If desired, the average of several rut depth measurements may be saved, greatly reducing the amount of storage required. In the past, SDDOT normally averaged twenty-five measurements to represent the rut depth on fifty foot intervals. Beginning in 1989, ten foot averages will be recorded.

Like profile data, rut depth measurements are stored on floppy disk for later analysis, including plotting and summary reports.

2.7 Visual Ratings

The Road Profiler's measurement software includes the ability to accept the operator's visual ratings of various road conditions. Its computer carries a file identifying the locations of about two thousand predefined rating sections on the state's highway system. Seven individual ratings are maintained for each section. The computer tracks the test vehicle's location on the highway while profile and rut depth are measured. The software determines which section the test vehicle is on, prompts the operator to update its ratings, and replaces old ratings with new. At the end of the testing season, the completely updated rating file is used to update SDDOT's pavement management database.

Any items which are observable at normal highway speeds, such as grade elevation, longitudinal drainage, and subgrade stability can be rated in this manner. The Road Profiler software allows users to define the item names and the par value associated with each item. This feature permits other states to decide which items to rate according to their needs.

The operator may also rate sections separately from profile and rut depth measurements. This is useful on urban sections, which are often too short to permit the operator to rate while measuring profile and rut depth.

2.8 Laboratory Computer Facilities

After profile and rut depth measurements are made, various computer programs may be used to analyse them. SDDOT has developed software to plot, summarize, and transfer information to a mainframe computer based pavement management system. This software may be run on the Road Profiler computer or on another similar computer permanently located in the laboratory. All software runs under RT-11, the standard single-user operating system available from Digital Equipment Corporation, or TSX+, a multi-user operating system similar to RT-11. (TSX+ is available from S&H Computing of Nashville, Tennessee.)

Several peripheral devices can be used to generate analysis documents. Profile plots and summary reports of roughness and rut depth can be printed on the dot-matrix printer in the test vehicle or on a higher speed dot-matrix printer in the laboratory. An eight-pen plotter in the laboratory can produce higher quality plots of profile, rut depth, and summary information.

All of the analysis programs utilize the profile, rut depth or visual survey data files which were created at the time of profile measurement.

2.9 Calibrations and Tests

The Road Profiler software includes various checks on performance to insure the integrity of measurements. Questionable ultrasonic measurements, identified by unreasonable values or excessive variations, are replaced by interpolation between known valid measurements. The number of replaced values is normally very small, less than one or two per thousand measurements. The accelerometer signal is also monitored to insure proper operation. Profile measurement terminates when an error is detected, and pertinent error messages are displayed.

In addition to these checks, small test programs are provided to individually test the accelerometer and ultrasonic sensors. These tests are performed as a daily check or as needed. Finally, the software allows the operator to change various parameters such as data recording intervals and sensor calibration factors. Calibration of the traveled distance sensor is accomplished by driving the vehicle a known distance.

CHAPTER 3

HIGHWAY AND LOCATION REFERENCE

If highway condition measurements are to be useful in a pavement management system, their location must be properly referenced to the highway system. Most state agencies maintain an inventory of highways and reference points or markers to which data must be referenced. Referencing of automatically recorded data can be difficult because distances measured by a test vehicle usually differ from distances listed in the inventory. Furthermore, it is probable that neither the measured nor inventory distances describe true distances with complete accuracy.

The Road Profiler handles the problem of matching measured distances to inventory distances by assuming that inventory distances are always correct. The Road Profiler computer carries the entire inventory of the state's highways and reference markers. The distances measured by the Road Profiler are stretched or squeezed slightly so profile and rut depth data fit the inventory distances. Recorded data locations are consistent with the inventory from the time of measurement on.

This method guarantees that locations assigned to test data will never contradict the inventory. This does not mean that inventory distances are never verified, however. In fact, one of the Road Profiler's secondary functions is to compare measured distances to inventory distances so probable errors can be identified.

The Road Profiler assumes certain conventions regarding highway names, reference markers, and location identifications. Although these conventions match SDDOT's formal policy, they are quite adaptable for other states' use.

3.1 Highway Names

The Road Profiler permits up to eight characters for highway identification. The first character--called "class"--is numeric, and defines the class to which the highway belongs. The remaining seven characters are alphanumeric, including blanks. They can contain any combination of characters which uniquely identify a highway.

The South Dakota Department of Transportation's highway numbering policy illustrates one way to use this highway identification scheme:

1. Class 1: In South Dakota, a "1" in the first character denotes a Class 1 highway--that is, a highway on the state system. Characters 2-4 identify the route number, which is unique in the state. Interstate, United States and South Dakota routes may not carry the same route number. Characters 5-7 contain optional suffixes which identify bypasses, frontage roads, divided highways, and other special attributes. The eighth character is unused.

2. Classes 2 & 3: Classes 2 and 3 signify county and municipal highways, respectively. For these highways, characters 2-3 identify the city or county number which is unique within the state. Characters 4-7 identify the route name, which is unique within the city or county. The eighth character is unused.

3. Class 4: Class 4 denotes Forest Service or other direct Federal routes. As with Class 1 highways, characters 2-4 identify the route number and characters 5-7 contain optional suffixes. The eighth character is unused.

To the Road Profiler, these definitions are entirely arbitrary. Any other naming convention with eight characters or less can be used instead. Every highway name must be unique, however, and no highway may have more than one name. If two routes run concurrently, one name must predominate over the other.

When the operator identifies a highway, the Road Profiler checks whether the highway exists in the state highway inventory. If not, the Road Profiler will refuse to perform measurements. One exception to this rule exists. If the first character of the highway name is "0", no validity checks are performed. The Road Profiler assumes that all

Class 0 highways exist, regardless of the remaining seven characters' contents. This feature allows roads which are not on the state's highway inventory to be tested for special purposes.

3.2 Reference Markers

The Road Profiler requires reference markers to identify known highway locations. In South Dakota, all highways on the state highway system are marked with Mileage Reference Markers (MRMs). Uniform MRMs, which are integer-valued, exist at intervals of approximately one mile throughout the highway's length (Figure 6). Non-uniform MRMs, which may have values to two decimal points, exist at the beginning and ending of every contiguous length of highway, at intersections with other highways, and at structure locations. By policy, all uniform MRMs are physically posted along the shoulder of highways. Non-uniform (non-integral) MRMs at intersections and major structures are usually posted.

Figure 6: Mileage Reference Marker

Locations on the highway are identified by positive or negative displacements from Mileage Reference Markers. For example, the point "20+0.500" is one half mile past MRM 20, while "32.25-0.125" is one-eighth mile prior to MRM 32.25.

MRM values increase monotonically from west to east on even-numbered (east-west) routes, and from south to north on odd-numbered (north-south) routes. By convention, odd numbered lanes travel in the direction of increasing MRMs, while even numbered lanes travel in the opposite direction. The lowest numbered lanes (lanes 1 and 2) are on the outside of the road.

Although Mileage Reference Markers resemble mileposts, they only approximate distance measurements. The distance between adjacent uniform MRMs is often less or greater than one mile. Where reconstruction has produced major alignment changes, the true distances between MRMs may be far different from the arithmetic difference between their values. MRM values are correctly interpreted as names, not distances.

Actual distances are computed from the MRM's "True Mileage", which is defined as the distance from the highway origin to the MRM. (These distances are measured to the thousandth of a mile by vehicles equipped with distance measuring devices.) Because the Road Profiler's inventory contains values and True mileages of every Mileage Reference Marker, it can compute distances between any two MRMs on a highway.

Because MRM values do not represent distances, equations are unnecessary. Therefore, no more than one MRM may exist at any location on a highway and no MRM value may exist at more than one location on a highway.

Where highways are concurrent, a special convention applies. MRMs exist and are posted only for the predominant highway. When two highways are concurrent for a distance of five miles, for example, the predominant highway's MRMs are physically posted on the highway. A five-mile gap in the subordinate highway's MRMs exists on the highway and in the inventory. Furthermore, True Mileage only accumulates for the predominant highway. The subordinate highway's True Mileages at the initial and final points of concurrency are identical, even though the MRM values at the two points differ by approximately five miles.

The software employed by the Road Profiler uses the conventions listed above, with one minor difference. While South Dakota policy only permits two decimal places (hundredths) in the MRM value, the Road Profiler will accept three (thousandths). This does not conflict with South Dakota's use, but allows other states to use three decimal places if desired.

The Road Profiler checks the validity of every Mileage Reference Marker identification made during data collection and analysis, except for Class 0 highways. Because Class 0 highways are by definition not contained in the inventory, validity checks are impossible. Because the True Mileages of Class 0 highways' MRMs are unknown, the Road Profiler assumes that they are identical to the MRM values.

3.3 Distance Measurement

The Road Profiler uses its own instrumentation to measure distance between and beyond Mileage Reference Markers. A standard magnetic sensor mounted between the test vehicle's transmission and speedometer cable generates electronic pulses at intervals of approximately 0.97 feet (Figure 7). An interface board located in the Road Profiler computer's backplane detects these pulses and multiplies their frequency by 512 (Figure 8). Each pulse then represents a distance of approximately 0.0019 feet.

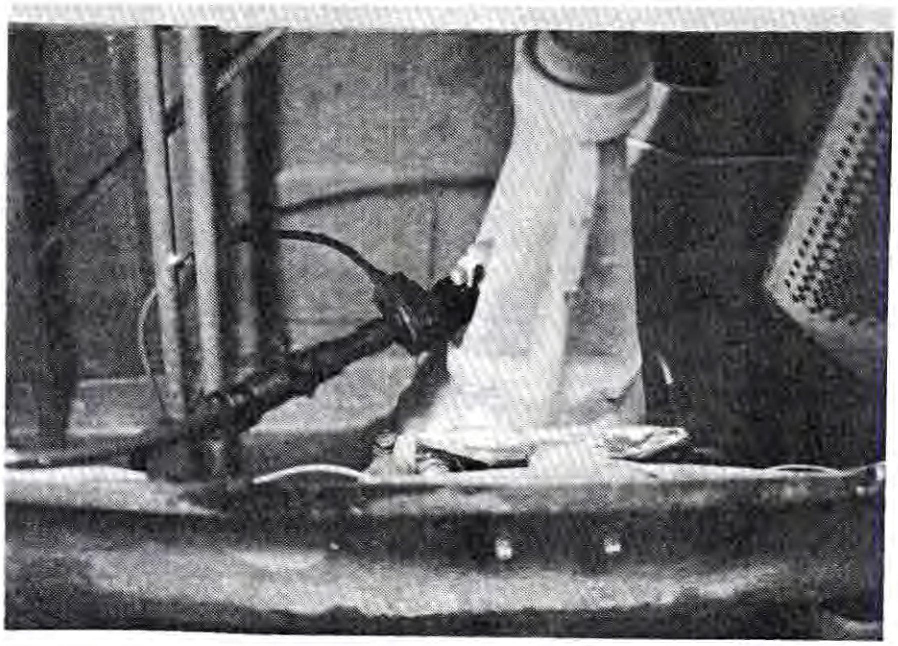


Figure 7: Magnetic Distance Sensor

A sixteen bit counter on the interface board accumulates the pulses until the count matches a software programmable count equivalent to the desired data interval. The interface generates a program interrupt which causes the software to

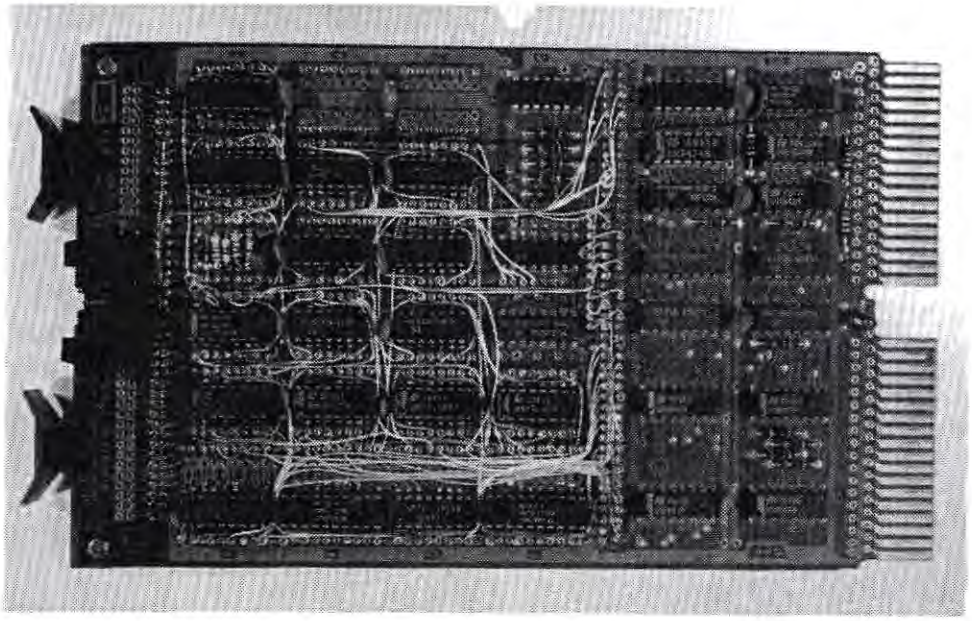


Figure 8: Distance Measurement Interface

update the traveled distance and initiate profile and rut depth measurements. Normally, an interval of one foot is specified, but other intervals may be selected so long as they are consistent with the operating speed of the system.

The Road Profiler software determines the distance calibration factor by counting the number of pulses required to travel a known distance. Calibration is required when the Road Profiler is first installed and periodically thereafter to correct for tire wear. With weekly checks for constant tire pressure, the accuracy of distance measurement is usually one-half percent or better.

Profile and rut depth measurements are associated with Mileage Reference Markers as the measurements are being taken. As the test vehicle travels down the highway, the operator identifies MRMs on the computer's handheld terminal. At the instant the vehicle passes the MRM, the operator strikes the "RETURN" key to record the MRM's value and position in the data stream. The accuracy of this process depends upon the operator's ability to strike the "RETURN" key at the correct instant. A practiced operator will consistently key within ten or fifteen feet of the correct location.

The Road Profiler uses distance measurement coupled with knowledge of the highway inventory to prevent testing off the end of highways. When the Road Profiler determines that it has reached the end of the highway, measurements automatically terminate.

The Road Profiler compares the measured distance between Mileage Reference Markers to the difference of their True Mileages listed in the inventory. Ratios significantly different than 1.000 indicate that either the distance measurement system is incorrectly calibrated or the inventory's True Mileages are in error. This information is used to make annual corrections to SDDOT's MRM inventory.

3.4 Rating Sections

When rut depth capability was added to the Road Profiler, the measurement software was enhanced to accept the operator's visual ratings. Prior to this time, SDDOT personnel had manually evaluated certain characteristics of contiguous, homogenous rating sections. Often, but not always, these sections corresponded to construction projects. The Road Profiler's software now operates similarly.

The Road Profiler computer carries a statewide inventory of visual ratings. The inventory contains the Mileage Reference Marker and displacement of each rating section's beginning and end. The name of each rating item and its par value are also in the inventory, as are previous rating values for each item. The names of the rating items are definable, permitting different states to rate different items.

As the Road Profiler measures profile and rut depth, it tracks the vehicle's location on the highway. When a new rating section is entered, the Road Profiler advises the operator. The limits of the section are displayed, as are the previous year's rating values.

The operator is free to update ratings when he is satisfied that his observations are complete. If the Road Profiler reaches the end of the rating section before the operator has made updates, the software requests that the operator rate the section immediately. When the operator has finished, the software informs him of the next rating section's limits and ratings.

Because some rating sections are very short, especially in urban locations, the operator may have insufficient time to observe and update ratings while profile and rut depth are being measured. On sections less than one-half mile long, the software advises the operator that a short section has been entered, but does not allow him to rate it. The operator must rate the section later, using another program which does not measure profile or rut depth.

At the end of the test season, those ratings which were updated are transferred back to the department's central data base.

3.5 Urban and Rural Boundaries

Since 1982, the South Dakota Department of Transportation has computed roughness ratings from profile measurements. These ratings have been used along with other ratings to prioritize highway construction and reconstruction needs.

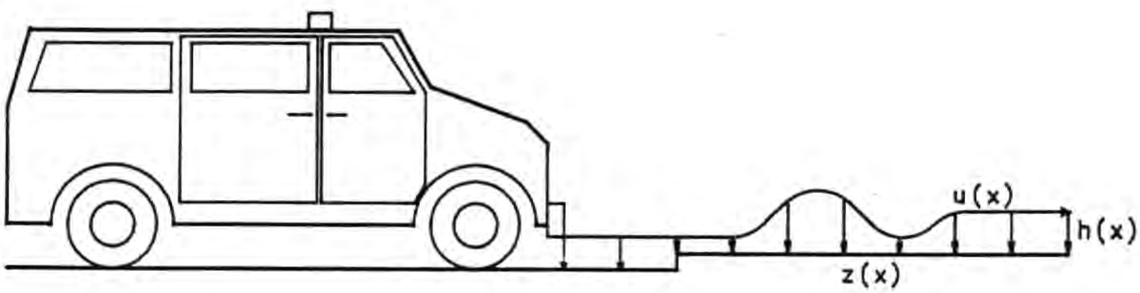
Because urban roads usually have frequent grade changes, especially at intersections, they are usually much rougher than rural roads. SDDOT's first attempts tended to prioritize urban highways too high. To overcome this problem, some of the analysis software was modified to compute roughness ratings differently for rural and urban highway sections.

The Road Profiler computer carries a statewide list of rural and urban boundaries, each identified by a Mileage Reference Marker and displacement. Roughness rating software computes higher Present Serviceability Indices for highway sections within urban limits. If this feature is not desired, all highways may simply be defined as rural.

CHAPTER 4

PROFILE MEASUREMENT AND ANALYSIS

The SDDOT Road Profiler is an "inertial" profile measurement device--that is, it utilizes an accelerometer to establish a reference plane from which the profile is measured. Figure 9 illustrates the principle of measurement.



h(x) – Vehicle Height Above Pavement

u(x) – Vehicle Position

z(x) – Vertical Road Profile

Profile = z(x) = u(x) – h(x)

Figure 9: Profile Measurement Principle

As the test vehicle moves in the horizontal direction x, it encounters the vertical roadway profile z(x). In response to the profile, the vehicle body moves vertically, as indicated by the curved line u(x). At every point along the vehicle's path, the difference between the road profile z(x) and the vehicle's vertical position $u(x)$ is $h(x)$, the distance between the vehicle body and the pavement surface. Stated mathematically,

$$h(x) = u(x) - z(x) \tag{2}$$

or equivalently,

$$z(x) = u(x) - h(x) \tag{3}$$

The significance of Equation 3 is that if $u(x)$ and $h(x)$ can be measured, the road profile $z(x)$ can be computed. This is true, regardless of the vehicle's suspension characteristics. For any vehicle response, $u(x)$ and $h(x)$ vary together, such that their difference equals the profile $z(x)$.

The Road Profiler determines the vehicle's vertical position $u(x)$ by numerically integrating a measured vertical acceleration signal. An ultrasonic sensor measures the distance $h(x)$ between the vehicle body and the pavement surface. The road profile $z(x)$ is computed as the numerical difference between $u(x)$ and $h(x)$.

Conceptually, the process can be divided into the six operations summarized by Figure 10. These are: 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 highway profile; storage of the computed profile; 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 is performed after the data is returned to the laboratory.

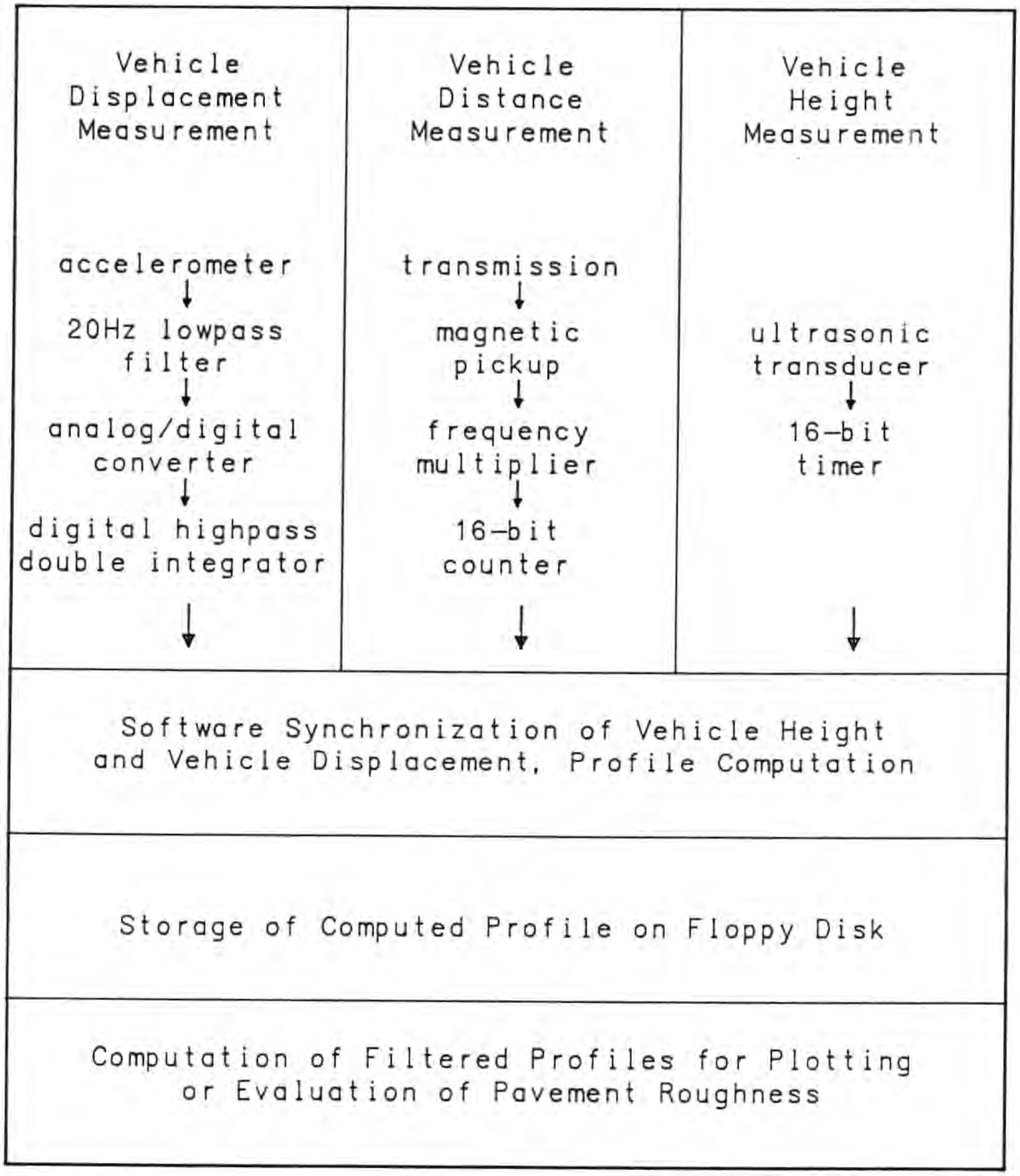


Figure 10: Profile Measurement Block Diagram

4.1 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 integrate the acceleration to generate the displacement record.

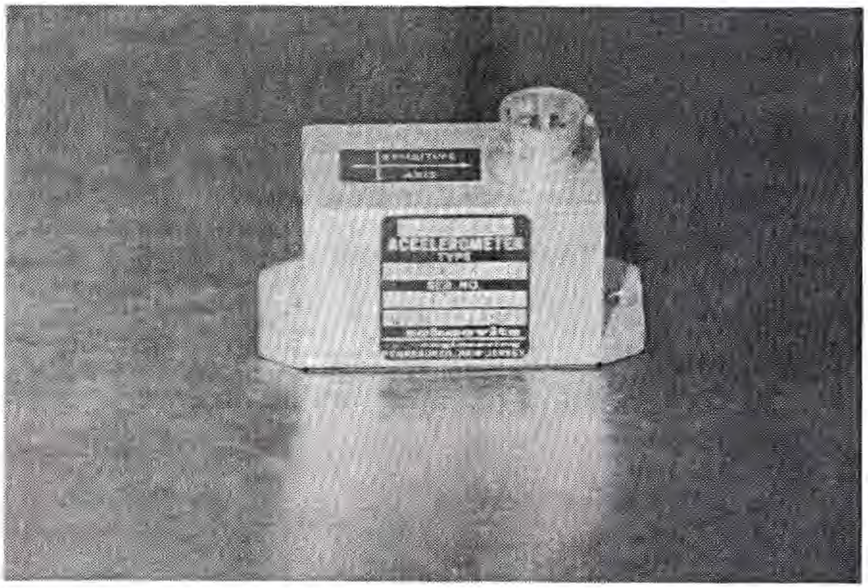


Figure 11: Linear Servo Accelerometer

A Schaevitz model LSBC-2 linear servo accelerometer (Figure 11) measures the vehicle's vertical acceleration. The unit is biased for one "g" to eliminate the acceleration due to earth's gravity from the signal output. Its range of plus or minus two "g" and frequency response of 0-110Hz are adequate to measure significant vehicle motions which fall in the range of plus or minus one "g" at 0-5Hz.

In addition to meaningful accelerations, the accelerometer signal contains high frequency components corresponding to extraneous vehicle body vibrations. A linear phase lowpass filter is used to attenuate these components. Sampling theory dictates that the filter eliminate frequencies higher than the Nyquist frequency, which is one-half the 125Hz sampling frequency. In practice, elimination of frequencies higher than one-fourth the sampling frequency is desirable. The filter should, however, pass frequencies of interest with as little attenuation as possible.

Figure 12: Accelerometer Antialiasing Filter

A Frequency Devices Model 757L8L 20Hz eight pole lowpass filter is mounted on a circuit board located within the Road Profiler computer (Figure 12). The board also carries an operational amplifier which multiplies the acceleration signal by a factor of two to increase the signal level to five volts per "g", and a bipolar fifteen volt power supply module which provides power to the accelerometer, filter module, and operational amplifier.

Figure 13 shows the attenuation and delay introduced by the lowpass filter. Below 2Hz, where the most significant vehicle accelerations occur, the signal loss is less than 0.7%. At 4Hz, the loss is approximately 2.7%. At 20Hz, the signal is attenuated by 50%, and at the Nyquist frequency of 62.5Hz, the signal is attenuated by 99.95%. The delay introduced by the filter is a nearly constant 25.3 milliseconds in the frequency range of 0-40Hz. Dela decreases to 12.3 milliseconds at 62.5Hz.

After the acceleration signal is filtered, it is converted into numbers which may be manipulated by the computer. An ADAC Model 1012 12-bit analog to digital converter installed

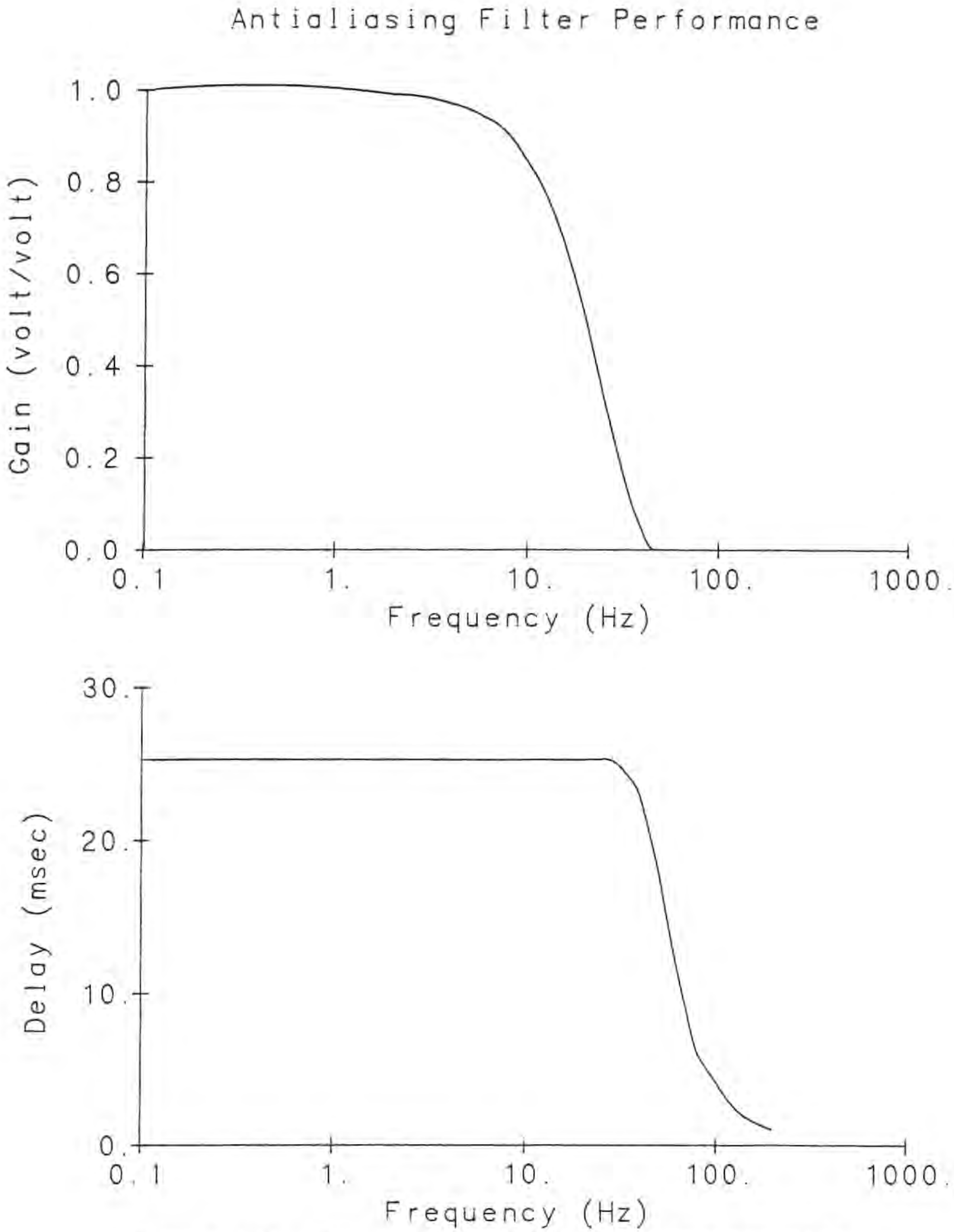


Figure 13: Antialiasing Filter Characteristics

in the computer digitizes the signal at 8 millisecond intervals, converting signal levels between -5 volts and +5 volts (corresponding to accelerations of minus one "g" and plus one "g") into integers between -2048 and +2048. The resolution of the acceleration signal is one "g" divided by 2048, or 0.01571 ft/sec^2. The a/d converter's stated accuracy is plus or minus 0.025% of full scale reading, or approximately one half its resolution.

Acceleration sampling must occur at precisely timed intervals to insure accuracy in the subsequent integration. Measurements are initiated by an ADAC Model 1601GPT clock programmed to generate interrupts at intervals of 8.00 milliseconds. 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 hardware and software are capable of sustaining the 125Hz sampling rate under any conceivable operating conditions.

The digitized acceleration signal is integrated twice to yield a record of vehicle displacement. The Road Profiler integrates numerically rather than with electronic circuits to avoid problems of integrator saturation.

The problem of offset errors is inherent to both analog and numerical integration. When an acceleration signal composed of a true time-varying acceleration a(t) plus some constant offset a_{off} is integrated twice, the computed displacement $u^*(t)$ consists of the true displacement u(t), one error term due to the initial (unknown) vertical velocity v_0, and another error term proportional to the square of time t. That is,

$$u^*(t) = u(t) + v_0 t + a_{off} t^2/2 \qquad (4)$$

It is evident that for even small offsets, the term involving t^2 predominates as time increases. For a profile ten miles in length, t^2 exceeds one half million seconds squared assuming a test speed of 50 mph. Even if the offset is only one thousandth of a "g", the displacement error is approximately 8300 feet, over 1.5 miles in elevation! Although the error term involving initial velocity v_0 is proportional to time and grows more slowly, it too can overwhelm the true displacement. Fortunately, because both error terms vary slowly, they can be controlled by removing extremely low frequencies from the integrated displacement signal.

A numerical process, a type of digital filter, simultaneously integrates and filters the acceleration signal as it is measured. The filter can be described by its transfer function which specifies the ratio of 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 highpass filtering transfer function H(f), where f is the frequency of the signal:

$$F(f) = I(f) * H(f) \tag{5}$$

The ideal double integrator transfer function

$$D(f) = -[1/(2*pi*f)]^2 \tag{6}$$

is numerically approximated by the transfer function

$$I(f) = -[h/2\sin(pi*f*h)]^2 \tag{7}$$

The quality of this approximation depends upon the signal frequency and the sampling interval h. The ratio of actual to ideal integration is given by the relationship

$$R(f) = I(f)/D(f) = [pi*f*h/\sin(pi*f*h)]^2. \tag{8}$$

This ratio is exactly one when the frequency is zero, but reaches a maximum value of 2.47 at the Nyquist frequency. At 5Hz, below which vertical acceleration signals of interest lie, the approximation overestimates the displacement magnitude by 0.5%. It is important to note that while the integration increasingly overestimates at higher frequency, the lowpass antialiasing filter so strongly attenuates with increasing frequency that no net overestimation occurs.

The highpass filtering transfer function is

$$H(f) = 1/[1 + \cot^2(pi*f*h)/\cot^2(pi*f_0*h) \tag{9}$$

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

The complete filter transfer function F(f), the product of I(f) and H(f), is accomplished as a second order recursive digital filter of the form

$$u_n = Au_{n-2} + Bu_{n-1} + Ch^2 a_{n-2} \tag{10}$$

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 at time t is given as a linear combination of the two previously computed displacements and the acceleration measured two sampling intervals previously.

The integration algorithm introduces a signal delay of two sampling intervals at all frequencies, so that the displacement computed at time t actually corresponds to the vehicle displacement at time t-2h. In addition, the highpass filtering introduces delay which increases rapidly as frequency decreases. Longwave vehicle displacement components are shifted significantly.

Figure 14 shows the composite effect of the highpass double integration, assuming a vehicle speed of 55 mph. The "gain ratio"--that is, the ratio of computed displacement to true displacement--varies within plus or minus two percent over the frequency range of 8Hz to 0.08Hz, corresponding to wavelengths of 10 feet to 1000 feet. At frequencies above 1Hz, the signal delay is nearly constant and equal to a distance equivalent to two sampling intervals, or about 1.3 feet. At lower frequencies, the signal delay increases significantly; at a frequency of 0.0114Hz, corresponding to a wavelength of 7000 ft, the signal delay exceeds 1000 feet.

The practical significance of Figure 14 is that for the sampling frequency, highpass frequency, and vehicle speed normally used by the Road Profiler, the highpass integration accurately estimates the amplitude of vehicle motion at wavelengths up to 1000 feet, but not without phase distortion and delay at longer wavelengths. Because the vertical motion of the vehicle is restricted to frequencies below 5Hz, the integration's overestimation at higher frequencies is insignificant.

Because the integration and filtering are time-based rather than distance-based, these wavelengths and distances depend on vehicle speed. Figure 15 is similar to Figure 14, 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.

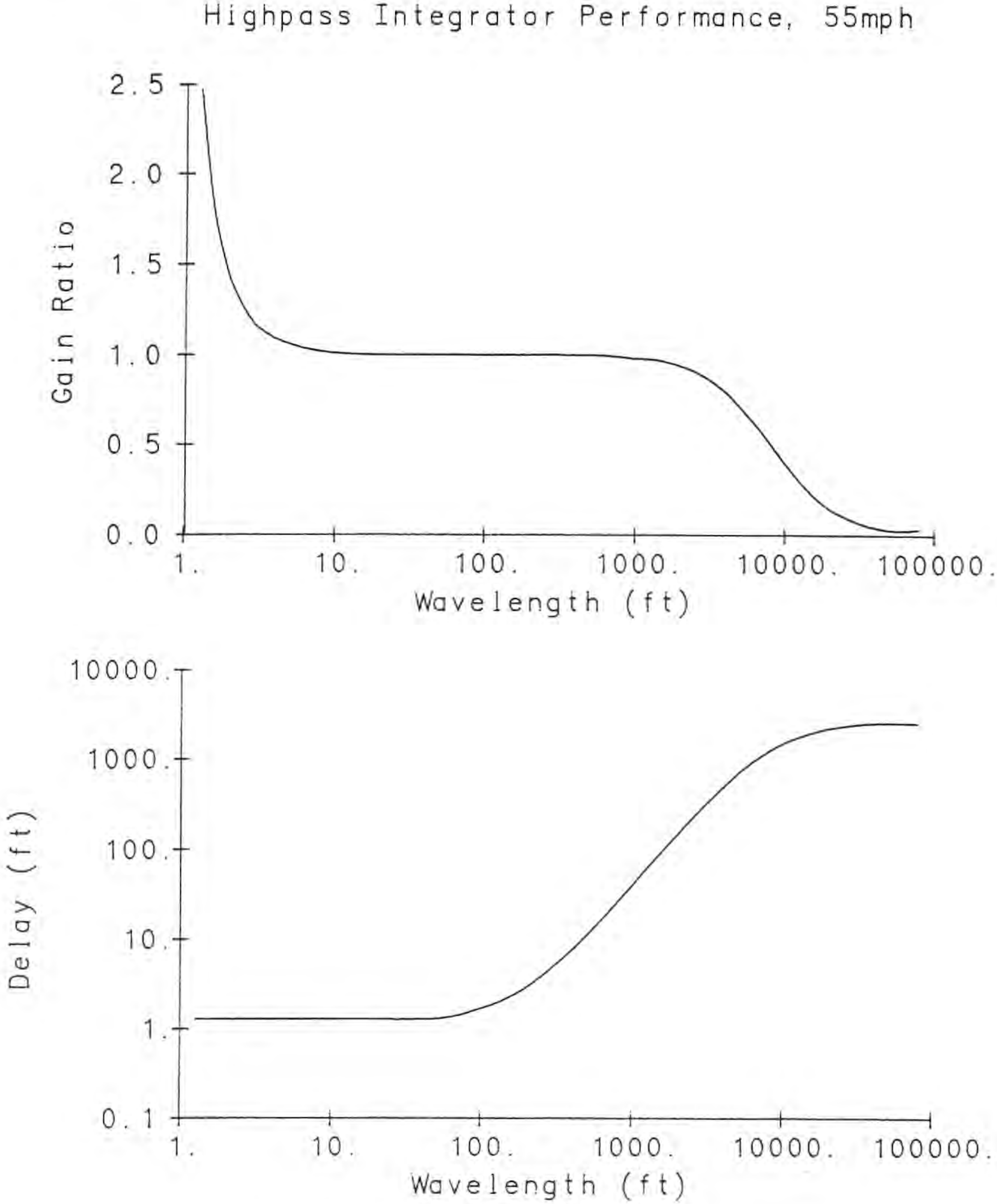


Figure 14: Highpass Integration, 55mph

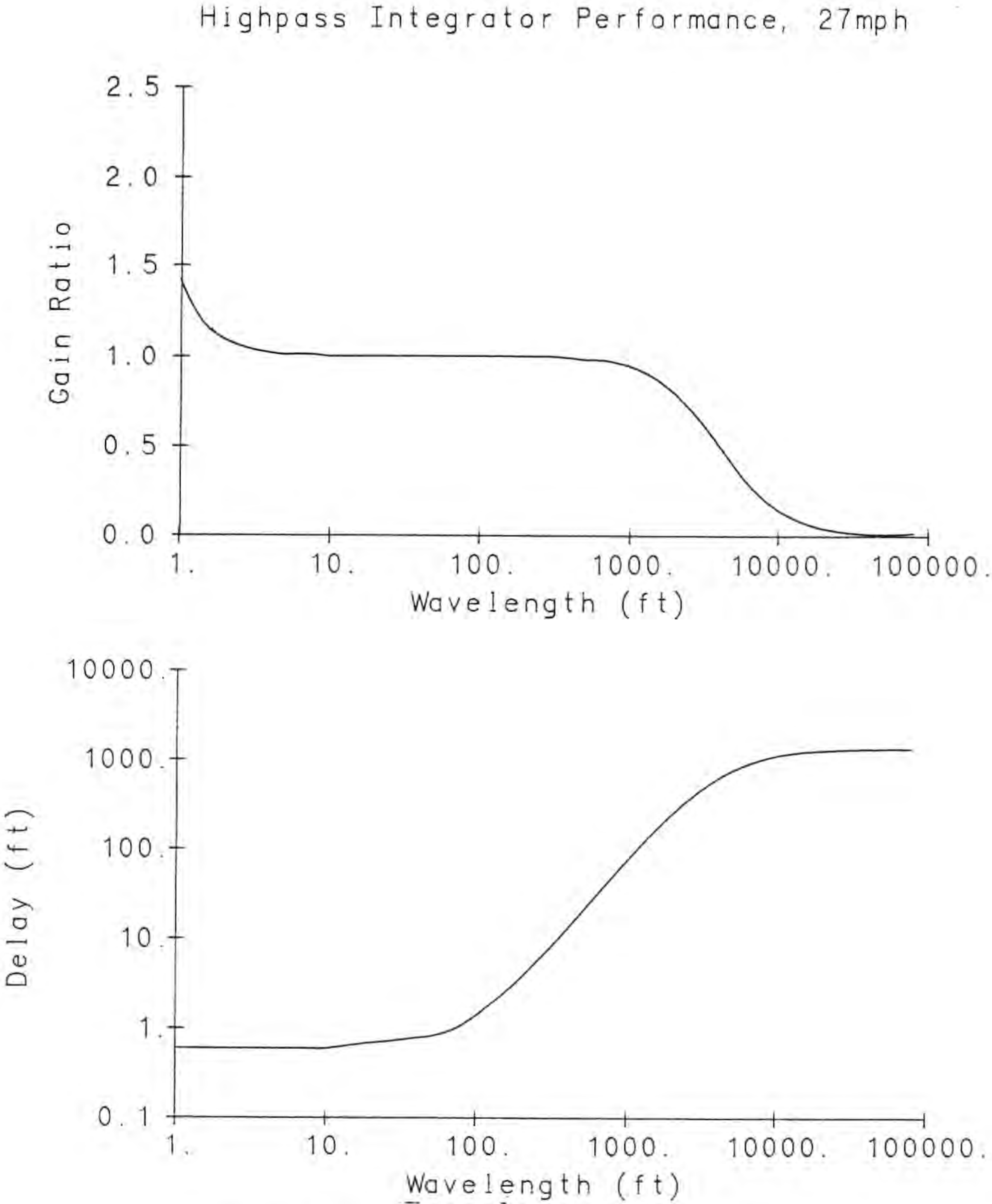


Figure 15: Highpass Integration, 27mph

4.2 Vehicle Height Measurement

The distance between the accelerometer and the pavement surface is measured by an ultrasonic ranging device mounted in the instrumentation bumper. The sensor (Figure 16) is based upon an instrumentation quality version of the electrostatic transducer used on autofocusing Polaroid cameras.

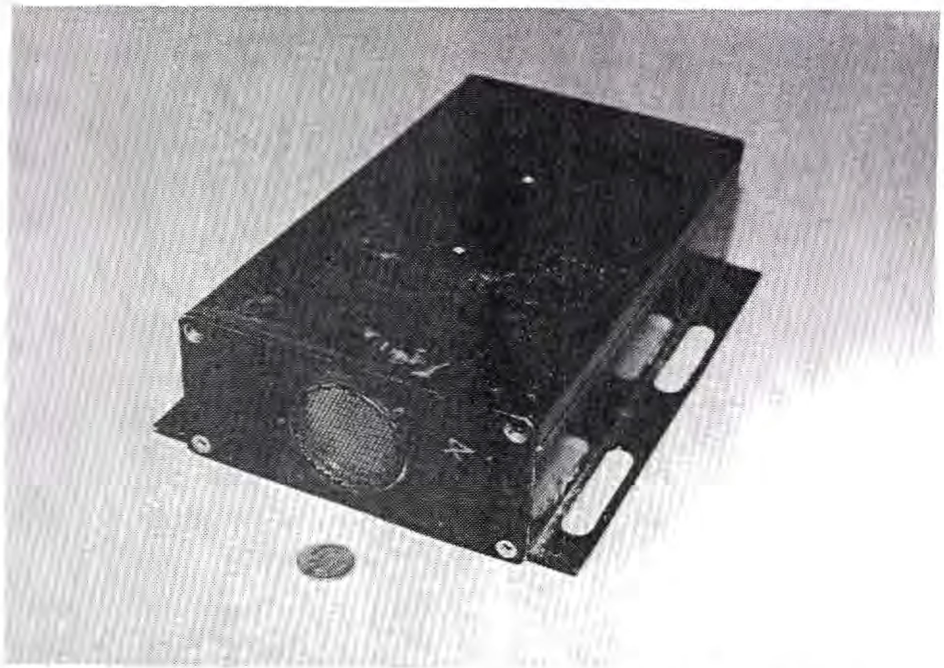


Figure 16: Ultrasonic Ranging Device

Its principle of operation is relatively simple; a short burst of 50KHz sound waves is generated by the transducer, travels downward to the pavement surface, and is reflected back to the same transducer (Figure 17). 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

$$t = 2h/c \tag{11}$$

where c is the velocity of sound in air, approximately 1125 feet per second. At the transducer's equilibrium position, approximately one foot above the pavement surface, the elapsed time is about 1.8 milliseconds. To prevent interference resulting from multiple echos, measurements must be performed at time intervals exceeding 10 milliseconds.

(a)
(b)
(c)

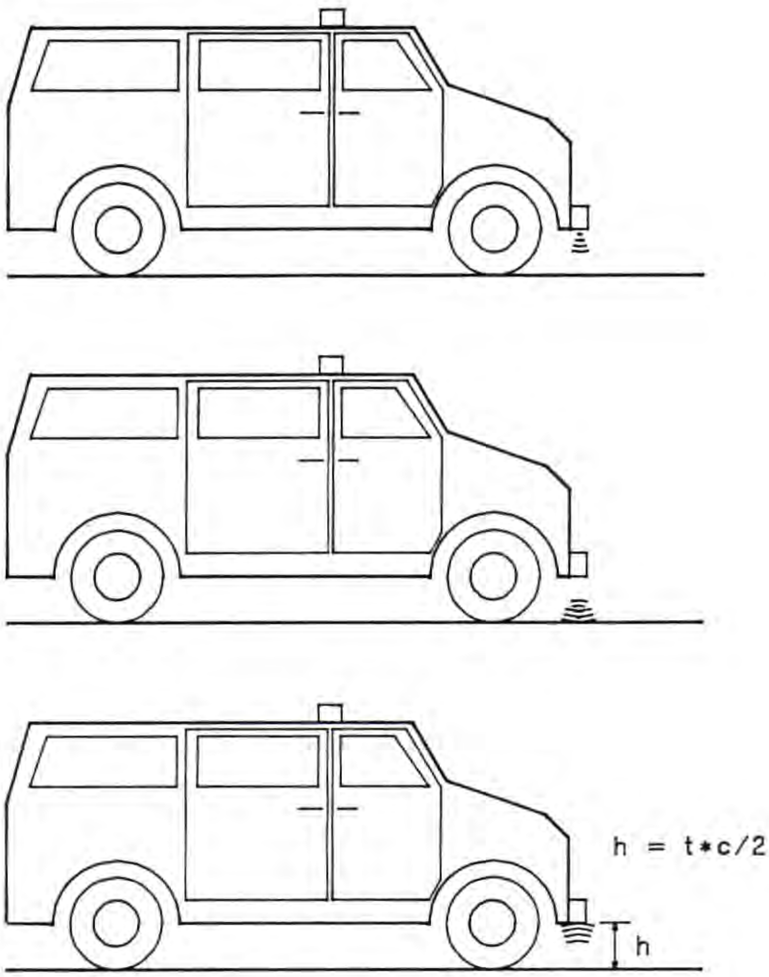


Figure 17: Ultrasonic Ranging Principle

Ultrasound generation, detection, and timing is controlled by an interface board installed in the computer (Figure 18). When the computer determines that the vehicle has traveled the specified sampling distance, software commands the interface to generate the ultrasound transmission. When the echo is detected, the interface provides a count representing the elapsed time interval accurate to one microsecond.

The transducer's "footprint" on the pavement surface is approximately four inches in diameter. Since timing stops upon receipt of the earliest echo, any large object (of cross section area exceeding one square inch or so) which protrudes above the surrounding surface may be detected instead of the background surface.

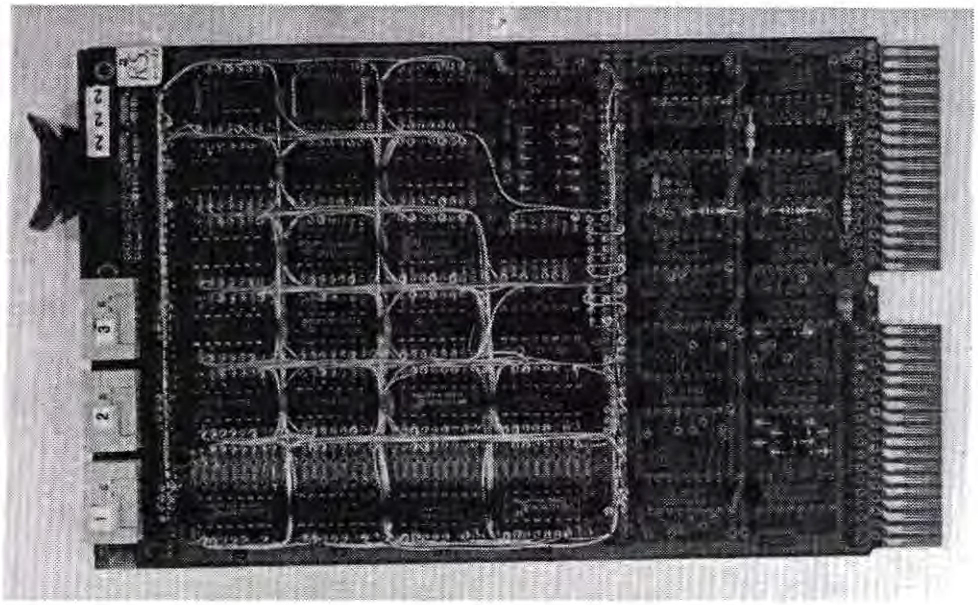


Figure 18: Ultrasonic Ranging Interface

Coarse surface texture can affect the measurement in two ways. First, there is inherent uncertainty in defining the distance between transducer and coarse pavements--which surface elevation is the correct one? Second, randomly oriented aggregate surfaces presented by coarse pavements may scatter the ultrasound or cause destructive interference, causing late echo detection. This problem occurs mainly on extremely coarse--5/8 inch or greater aggregate size--chip seals. Smaller chips, cracks, open graded asphalt mixes, and tined concrete do not cause excessive difficulty. Although timing accuracy allows measurement resolution of 0.001 feet, pavement surface effects limit accuracy to 0.005 feet on smooth pavement surfaces and 0.010 feet on very coarse surfaces.

During the time between signal transmission and echo detection, a vehicle traveling 55 mph moves forward approximately 1.7 inches, a distance slightly greater than the transducer's diameter. No correction is made to compensate for the oblique sound path because correction would be speed dependent and precise identification of the transmission, reflection and reception surfaces is impossible.

Likewise, no attempt is made to correct the distance measurement for effects of air temperature on sound velocity. Air temperatures vary tremendously with height above the pavement surface. Accurate temperature compensation would be 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. As a result, short features are incorrectly interpreted as features longer than twice the sample interval. This phenomenon--termed "aliasing"--is most severe when the profile has a high short wavelength content. In general, the computed International Roughness Index for such profiles will be higher than it should be. Aliasing can only be eliminated by decreasing the sampling interval. Because the ultrasonic sensors' sampling frequency is limited to 100Hz, the only way to shorten the interval is to decrease vehicle speed. This is almost never done in practice. Instead, errors are accepted.

4.3 Synchronized Profile Computation

Because the times at which vehicle position and vehicle height are measured generally do not match, the software must merge the two records and compute the profile as their difference

$$z(x) = u(t) - h(x). \tag{12}$$

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

The situation is complicated by delays--25 milliseconds in the analog lowpass filter and 16 milliseconds in the integration--which are introduced into the vehicle displacement record. These delays prevent the vehicle position from being available until approximately 40 milliseconds after the vehicle height measurement is completed.

The software overcomes this difficulty by saving vehicle height measurements, along with their 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 mismatch of 4 milliseconds is negligible because of the low frequency content of the vehicle displacement record.

4.4 Data Storage

The computed profile is stored on one of the 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 the elevation difference between succeeding points (in arbitrary units of resolution) are recorded. Deviations between adjacent points are limited to plus or minus one hundred twenty-seven times the resolution unit. For the Road Profiler, this equates to plus or minus 0.254 feet.

With this scheme, a 512 kilobyte diskette contains approximately 90 miles of profile sampled at one foot intervals. SDDOT's annual survey of approximately 8500 lane miles consumes approximately fifty two-sided diskettes.

4.5 Profile Reconstruction

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

$$H(w) = 1 / [1 + \cot^2(pi*h/w)/\cot^2(pi*h/w_0)] \qquad (13)$$

This filter is a spatial lowpass 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 highpass filter employed in the double integration, is of the form

$$p_n = Az_n + Bz_{n-1} + Cz_{n-2} + Dp_{n-1} + Ep_{n-2} \qquad (14)$$

That is, the filtered profile p is computed recursively as a linear combination of the unfiltered profile z at the present location and the filtered and unfiltered profile two data intervals previous. The coefficients A through E depend upon the data interval and cutoff wavelength.

Because the filter is recursive, the signal phase and delay become exaggerated at wavelengths near to and greater than the cutoff wavelength. Figures 19 and 20 show the filter's transfer functions with cutoff wavelengths of 1000 and 50 feet.

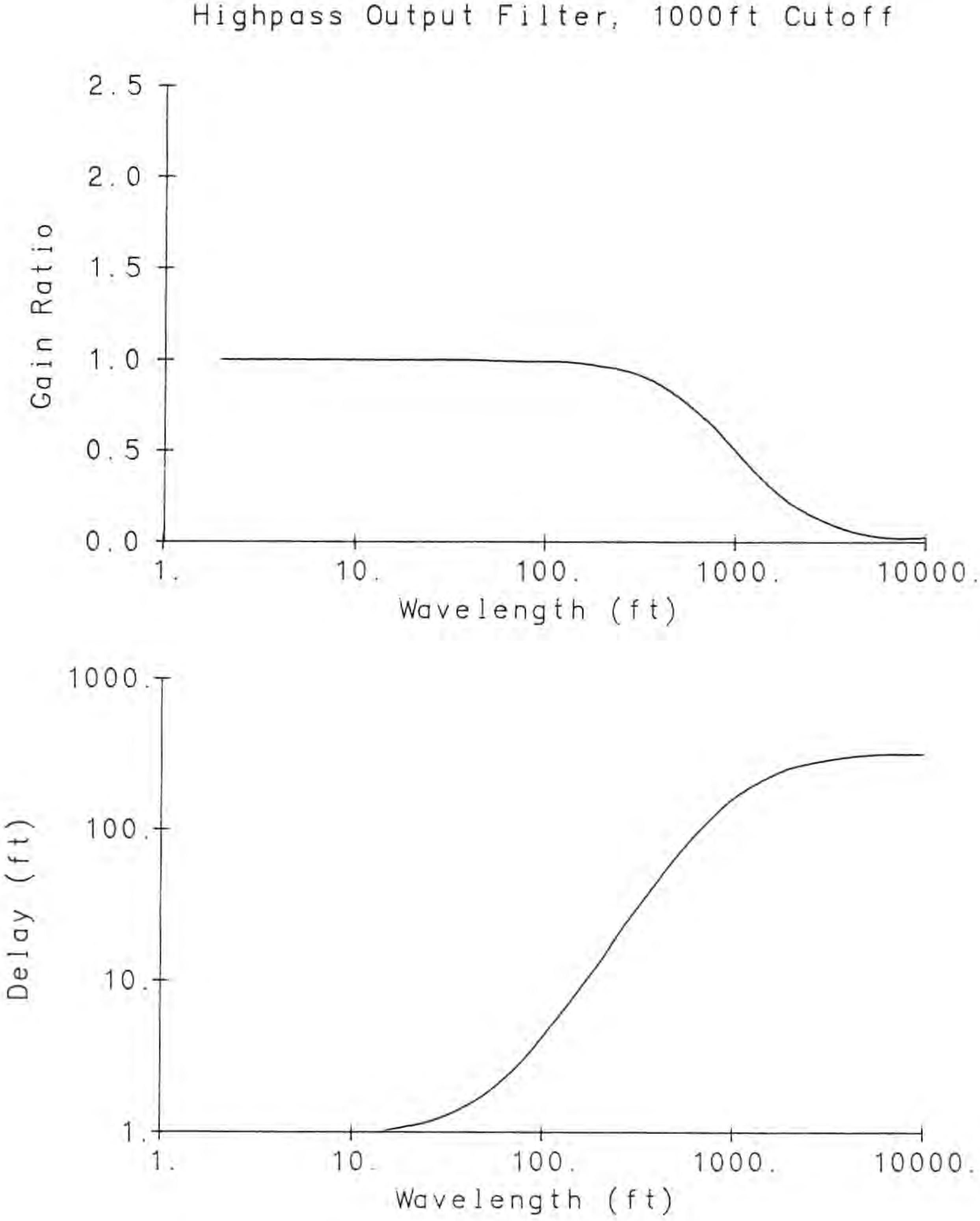


Figure 19: Highpass Filter, 1000' Cutoff

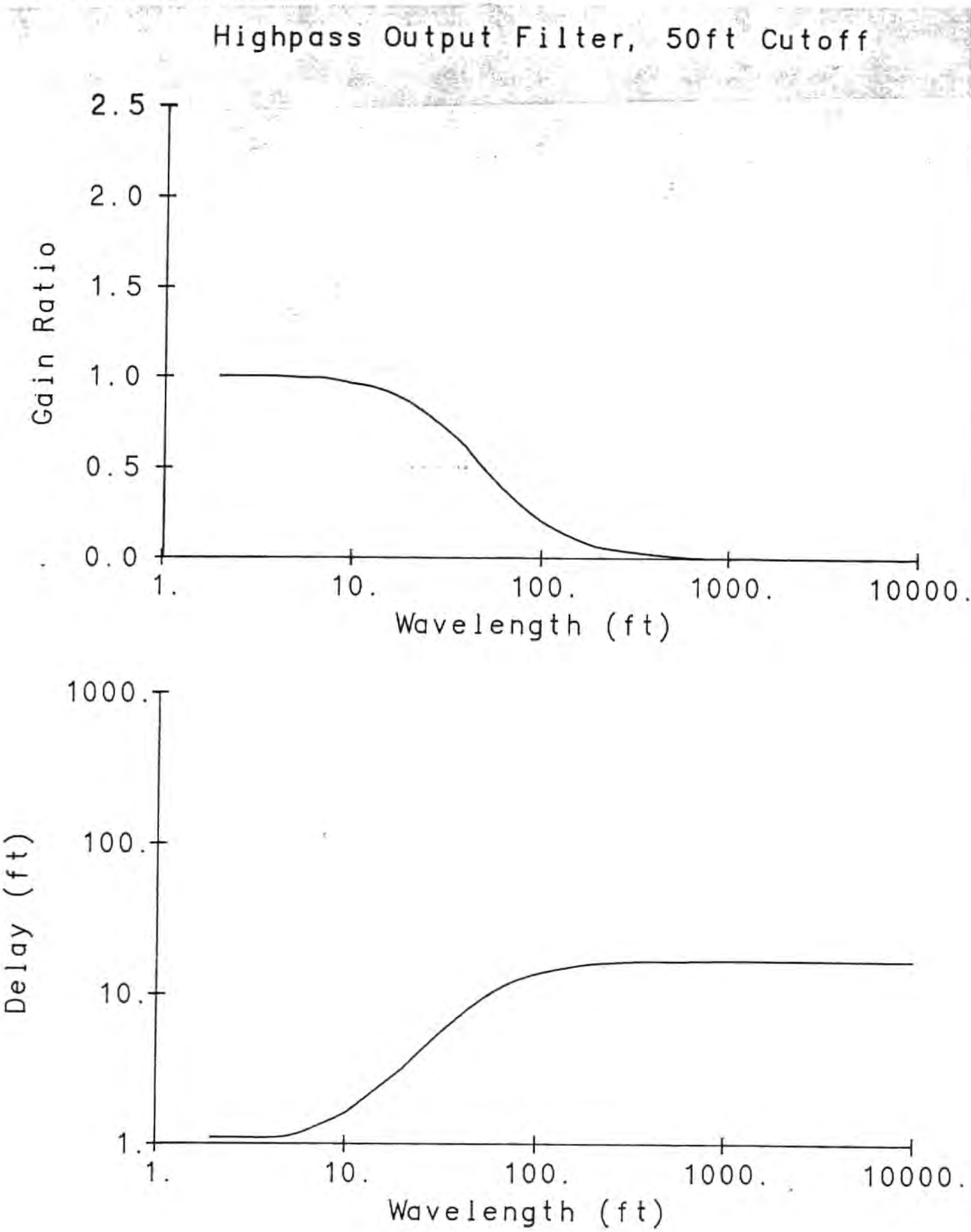


Figure 20: Highpass Filter, 50' Cutoff

4.6 Profile Plots

The most elementary analysis of roadway profiles is visual inspection of a plotted profile. Visual inspection quickly reveals the general character of the measured profile, and just as importantly, gives good indication of proper equipment operation.

Two types of computer generated plots are available. The first (Figure 21) produces simple profile plots on dot matrix printers. Although dot matrix printers are slow and produce relatively low quality plots, they are convenient and inexpensive. One difficulty with this technique is that each printer utilizes a unique graphics generation protocol requiring specialized graphics software. SDDOT has written dot matrix graphics subroutines for Okidata 80, 180 and 190 and Printronix 300 and 600 series printers, and plans to write sofware for Epson dot-matrix and Hewlett Packard laser printers in the future.

Alternatively, a pen plotter can be used to generate more complex, high quality plots at much higher speeds (Figure 22). Unlike most dot matrix printers, a pen plotter can move in any direction on the paper, greatly simplifying generation of elaborate drawings. Pen plotters usually have much better resolution, and because they draw continuously with an ink pen, drawings are not grainy like those produced by a dot matrix printer. Pen plotting software also offers more versatile scaling options than does printer software. It also allows multiple profiles to be plotted on the same reference axis, so measurements in different lanes or at different times can be compared. The Road Profiler software uses industry standard subroutines which provide basic plotting functions, such as point, line, and text drawing. These subroutines are supplied by the plotter's manufacturer.

Both plotting modes allow selected portions of roadway profiles to be plotted. The operator can specify the limits of his interest by MRM and displacement. Only the profile lying between the limits will be plotted.

When profiles are plotted, they are shown above or below a reference line. The line provides a scale of horizontal distance, but is meaningless in terms of absolute elevation. To illustrate this concept, a point which lies two inches above the line at MRM 30 is almost certainly not four inches higher than a point which lies two inches below the line at MRM 31. Because long wavelengths have been removed during profile recording and reconstruction, the information needed to relate elevations of points horizontally separated by

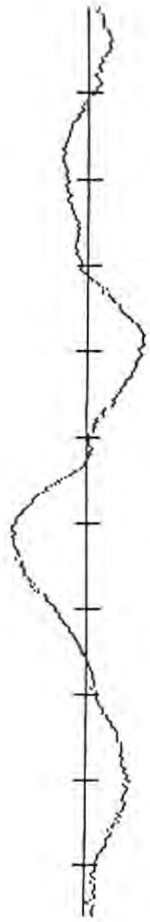
PRF010: Filtered Profile Plot
03-APR-89 08:17:43

Highway: 1034
Lane: 1
Project: SD 34 EAST OF PIERRE
Remarks: CLEAR & SUNNY
Date: 23-MAR-89
Time: 15:30:45

Test Vehicle: TBN555
Average Speed(mph): 54.952
Data Interval(ft): 1.000
Resolution(ft): 0.002
# of Data Points: 528
# of Bad U/S Data: 0

Filtered Profile Plot
Highpass wavelength: 500.00
Profile 0.25 Times Actual Scale

MRM Displacement
213.00 0.0000



213.00 0.1000
Disk: 35
File: 034000.213
Operators: JB & BL

Figure 21: Dot Matrix Printer Profile

PRF011: Filtered Profile Plot Program

Copyright 1986 SDDOT

Highway: 1034   From 213.00 + 0.00 to 213.00 + 0.10

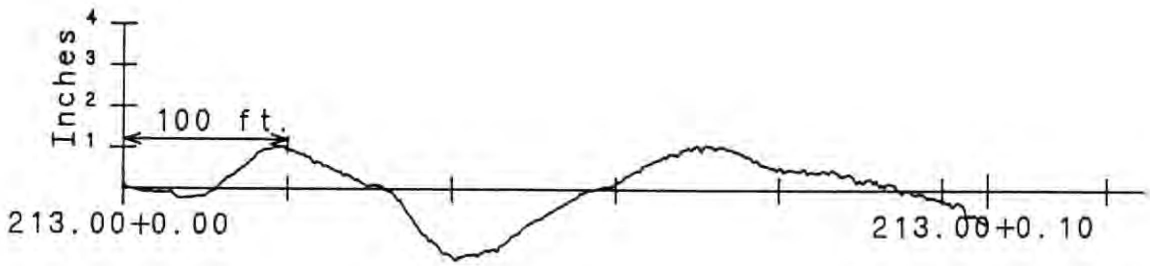


Figure 22: Pen Plotter Profile

more than a few hundred feet is lost. Actually, the information was never present, because of limitations in the sensitivity and accuracy of the acceleration measurement.

4.7 International Roughness Index

One of the most common analyses of profiles is computation of an index to rate the severity of roughness experienced by a vehicle traveling on the roadway. This computation is often done by numerically simulating the response of a generic vehicle--with standard mass, spring constants, and damping constants--to the profile. To simplify the computation, only one corner of the vehicle is considered, leading to the term "quarter-car simulation". The index obtained from this simulation is usually expressed in "inches per mile" of roughness.

In 1982, a study on road roughness commissioned by the World Bank proposed definition of an International Roughness Index (IRI) based upon the quarter-car simulation, but reported in metric units of millimeters/meter or meters/kilometer (1). Because this index has the potential of wide acceptance among the international pavement evaluation community, SDDOT has written software to compute the IRI from profiles measured by the Road Profiler. Figure 23 shows computed indexes for a moderately rough road.

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(1) Sayers, M. W., Gillespie, T.D., and Queiroz, C., The International Road Roughness Experiment: Establishing Correlation and a Calibration Standard for Measurements, World Bank Technical Paper No. 45, Washington, DC, 1986.

PRF022: International Roughness Index Document

03-APR-89 08:20:52

Highway: 1034
Lane: 1
Project: SD 34 EAST OF PIERRE
Remarks: CLEAR & SUNNY
Date: 23-MAR-89
Time: 15:30:45

Test Vehicle: TBN555
Average Speed(mph): 54.952
Data Interval (ft): 1.000
Resolution(ft): 0.002
# of Data Points: 528
# of Bad U/S Data: 0

MRM	From Disp	To Disp	IRI (m/km)	Very Good 0 1 2 3 4 5 6 7 8 9 10 Very Poor
213.00	0.000	0.005	1.16	*******
	0.005	0.010	1.33	********
	0.010	0.015	1.27	*******
	0.015	0.020	1.56	*********
	0.020	0.025	1.34	********
	0.025	0.030	1.56	*********
	0.030	0.035	1.92	***********
	0.035	0.040	2.51	**************
	0.040	0.045	1.91	***********
	0.045	0.050	1.43	********
	0.050	0.055	0.84	*****
	0.055	0.060	1.23	*******
	0.060	0.065	2.09	***********
	0.065	0.070	2.69	**************
	0.070	0.075	1.25	*******
	0.075	0.080	2.32	*************
	0.080	0.085	2.57	**************
	0.085	0.090	2.68	**************
	0.090	0.095	2.20	************
	0.095	0.100	3.11	*****************
Project Average			1.85	**********

Disk: 35
File: 034000.213
Operators: JB & BL

Figure 23: International Roughness Index Document

4.8 Present Serviceability Index

Prior to development of the Road Profiler, SDDOT used a response type meter to evaluate pavement roughness. At that time, a roughness rating between zero (an infinitely rough pavement) and five (a perfectly smooth pavement) was computed from the recorded vehicle suspension movement. This rating, conceptually similar to the Present Serviceability Index, was computed for each quarter mile interval on the state highway system and used in the state's pavement management system.

To maintain consistency after the Road Profiler was developed, a computational procedure was devised to transform road profile measurements into 0-5 roughness ratings. Simply stated, the process filters the profile to remove wavelengths longer than fifty feet, then computes the root mean square displacement R of the remaining profile. Finally, a 0-5 rating is computed according to the formula

$$PSI = 5\,e^{-\{[\ln(R)+6.71]/2.19\}^3} \tag{15}$$

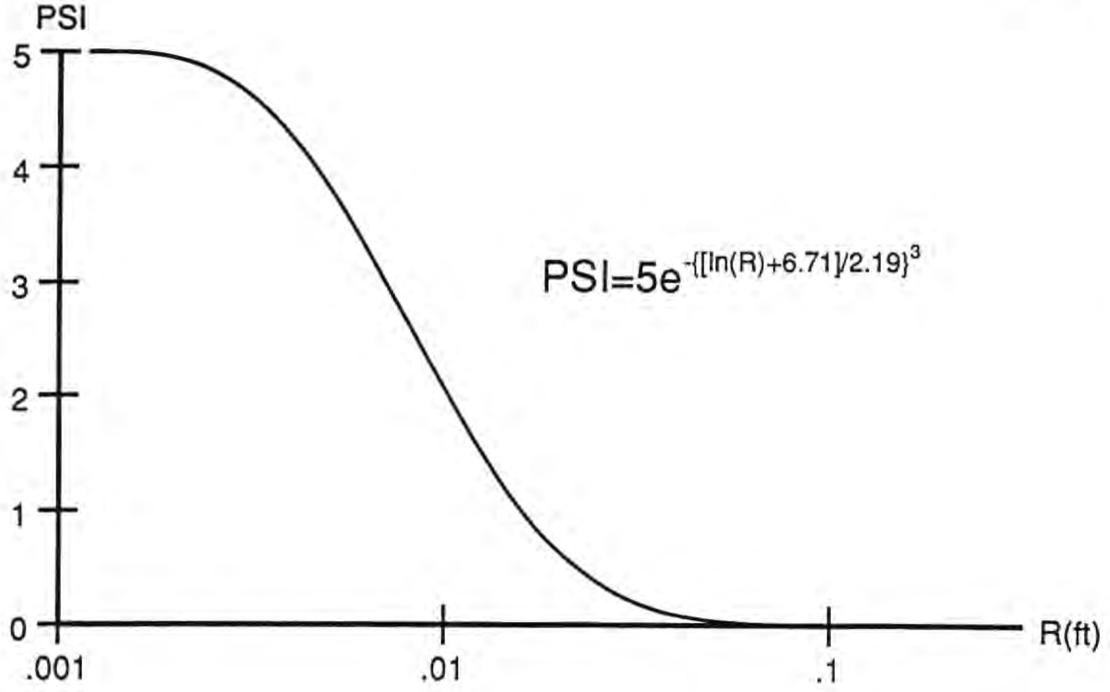


Figure 24: Present Serviceability Index Formula

This formula, which was determined empirically from comparisons between profiles and panel ratings in 1982, is illustrated by Figure 24. It produces indexes which fit pavement conditions and expectations in South Dakota. The computed indexes may not relate to other states' values, however.

A modification to this method is used on non-interstate urban roads, where intersections and other grade changes contribute significantly to the computed roughness ratings. Filtering urban profiles to thirty-two foot wavelengths instead of fifty results in roughness ratings which agree better with subjective roughness ratings. This procedure may be justified on the basis that vehicles drive more slowly in urban areas, so longer wavelength roughness is less significant. Viewed in this way, the adjustment corresponds to assuming traffic speeds of 35 mph rather than 55 mph.

The software allows selection of the project beginning and ending locations, as well as the distance interval over which ratings are computed (Figure 25). Urban highway sections are automatically recognized from information stored in the Mileage Reference Marker Inventory.

PROFILE MEASUREMENT AND ANALYSIS
Present Serviceability Index

PRF020: Roughness Rating Document Copyright 1986 SDDOT
03-APR-89 08:27:22

Highway: 1014
Lane: 1
Project: 4-CORNERS TO FT.PIERRE
Remarks: VERY WINDY
Date: 17-MAY-88
Time: 17:20:28

Test Vehicle: TBN555
Average Speed(mph): 55.675
Data Interval (ft): 1.000
Resolution(ft): 0.002
# of Data Points: 194586
# of Bad U/S Data: 63

MRM	From Disp	To Disp	PSI	Very 5 Good 4 Good 3 Fair 2 Poor Very 1 Poor 0
223.00	0.000	0.100	3.10	****************
	0.100	0.200	3.81	***********
	0.200	0.300	3.81	***********
	0.300	0.400	4.06	*********
	0.400	0.500	3.48	*************
	0.500	0.600	3.42	**************
	0.600	0.700	3.84	**********
	0.700	0.800	3.68	************
	0.800	0.900	4.28	*******
	0.900	1.000	4.44	*****
224.00	0.000	0.100	4.18	********
	0.100	0.200	3.83	**********
	0.200	0.300	3.44	*************
	0.300	0.400	4.09	********
	0.400	0.500	3.78	***********
	0.500	0.600	4.50	*****
	0.600	0.700	4.17	********
	0.700	0.800	4.10	********
	0.800	0.900	4.24	*******
	0.900	1.000	4.03	*********
Project Average			3.81	**********

Disk: 20
File: 014000.190
Operators: SINGH & STEWART

Figure 25: Present Serviceability Index

4.9 Spectral Analysis

Although single index roughness ratings are convenient for purposes of generalization and entry into large pavement management data bases, no single index discriminates between roughness of different wavelengths. It is possible for two pavement sections to have identical roughness ratings (either IRI or PSI), but to have entirely different roughness characteristics. One may be characterized by short, choppy roughness resulting from slab faulting while the other may be characterized by longer roughness resulting from subgrade instability.

A better description of roughness is given by specifying the spectral content of the profile. Any signal (in general terms, a measured profile is a signal) may be represented as a sum of sinusoidal components of various wavelengths. The signal can be described by specifying the intensity of each of these components. For example, the profile of a faulted concrete pavement with constant fifteen foot joint spacing will have intense signal components at wavelengths equal to multiples of the fifteen foot joint spacing. A power spectral density plot would display peaks at these wavelengths. Figure 26 shows an example of a spectral density plot plotted by the pen plotter.

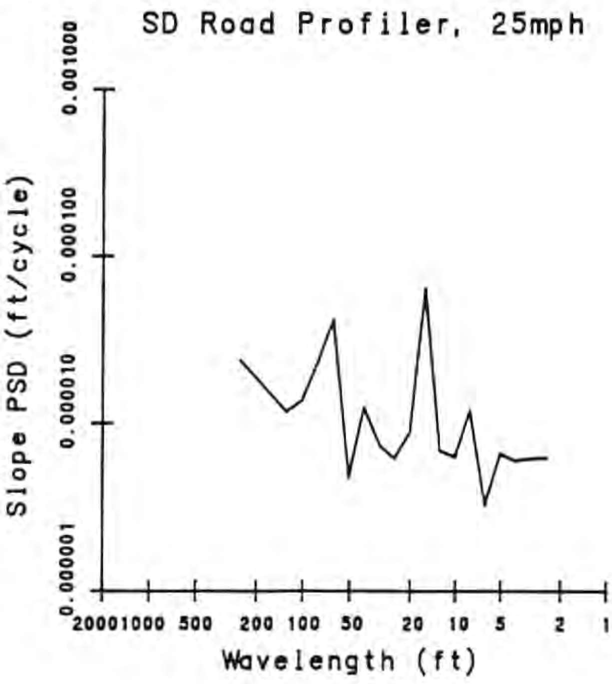


Figure 26: Spectral Density Plot

4.10 Mainframe Interface

After roughness ratings are computed, they are transferred to a central highway database residing on a mainframe computer. The South Dakota Department of Transportation has written software to generate update instructions specifically for its own database. Data are transferred via floppy diskette or serial interface.

Highway		MRM DSP	Date	Lane	IRI*10(mm/m)
1014	B	095000+0000	880531	1	039
1014	B	095000+0100	880531	1	020
1014	B	095000+0200	880531	1	020
1014	B	095000+0300	880531	1	016
1014	B	095000+0400	880531	1	023
1014	B	095000+0500	880531	1	024
1014	B	095000+0600	880531	1	024
1014	B	095000+0700	880531	1	021
1014	B	095000+0800	880531	1	015
1014	B	095000+0900	880531	1	014
1014	B	096000+0000	880531	1	015
1014	B	096000+0100	880531	1	014
1014	B	096000+0200	880531	1	013
1014	B	096000+0300	880531	1	011
1014	B	096000+0400	880531	1	023
1014	B	096000+0500	880531	1	018
1014	B	096000+0600	880531	1	015
1014	B	096000+0700	880531	1	015
1014	B	096000+0800	880531	1	016
1014	B	096000+0900	880531	1	015
1014	B	097000+0000	880531	1	013
1014	B	097000+0099	880531	1	012
1014	B	097000+0198	880531	1	012
1014	B	097000+0298	880531	1	014
1014	B	097000+0397	880531	1	013
1014	B	097000+0496	880531	1	014
1014	B	097000+0595	880531	1	015
1014	B	097000+0694	880531	1	024

Figure 27: IRI File Format

SDDOT has also written generic data transfer software for other states' use. Roughness ratings are computed for intervals of specified length, typically one tenth of a mile. Each interval's highway number, beginning (specified as a Mileage Reference Marker and displacement), and roughness rating are written to a file which may be transferred to a mainframe computer. Figure 27 illustrates the format of a file containing International Roughness Index Ratings.

RUT DEPTH MEASUREMENT AND ANALYSIS

CHAPTER 5

RUT DEPTH MEASUREMENT AND ANALYSIS

In the mid-1980's, South Dakota (like many other states) began to observe increased rutting on its highways. Because manual methods of rut depth measurement were slow and dangerous to personnel, the Road Profiler was modified to measure rut depth simultaneously with profile. Annual statewide rut depth surveys have been conducted since 1986.

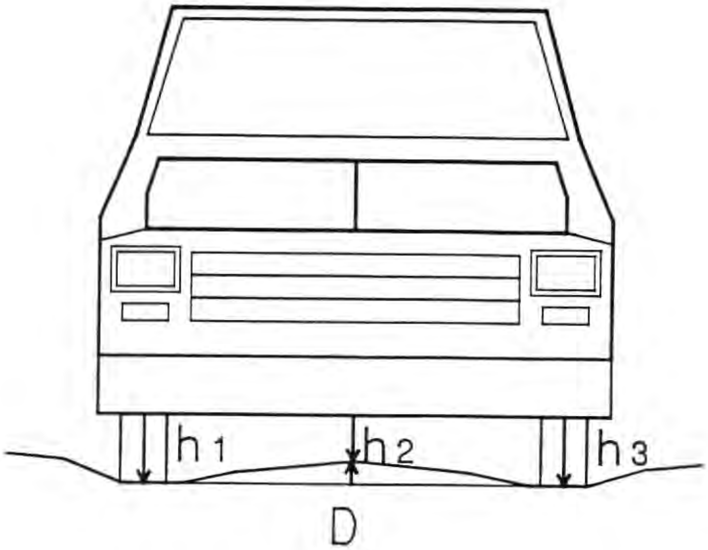
5.1 Rut Depth Measurement

The Road Profiler's method of rut depth measurement is illustrated by Figure 28. Three ultrasonic ranging devices are positioned in the test vehicle's instrumentation bumper. They are colinear and equidistant from each other, spaced 34 inches apart to match highways' predominant rut spacings. At every other profile measurement point, the three sensors measure the distance to the pavement surface. A quantity which approximates the average of left and right rut depth is computed according to the relationship

$$R = (h_1 - 2h_2 + h_3)/2 \tag{16}$$

where h_1, h_2 and h_3 are the respective distances between the pavement and the left, center, and right sensors. R actually represents the height of the hump between the wheelpaths.

When rut depth measurement capability was added to the Road Profiler, a five sensor system was initially proposed. This arrangement would have had the advantage of allowing separate left and right rut depth measurements, but would have required that sensors be mounted outside the wheelpath sensors. The three sensor system was chosen because of its simplicity and to avoid problems associated with overwidth vehicles.



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

Figure 28: Rut Depth Method

The basic accuracy of the rut depth measurement has been verified to be approximately one-sixteenth of an inch if the test vehicle maintains an accurate course with the sensors positioned above the wheelpaths. Certain factors can affect this accuracy, however. The three-sensor system cannot detect asphalt pavement which has shoved upward adjacent to the rut, so rut depths may be underestimated. Measurements in "dual wheel" ruts caused by heavy trucks on soft pavements are also less precise. In practice, these conditions do not pose a severe problem. Even though the measured rut depth is slightly inaccurate, a rutting problem is still clearly indicated.

Although rut depths are typically measured at two foot intervals, it is not necessary to record every rut depth measurement. If desired, the average of several rut depth measurements may be saved, greatly reducing the amount of storage required. In the past, SDDOT normally averaged twenty-five measurements to represent the rut depth on fifty foot intervals. Beginning in 1989, ten-foot averages will be recorded to satisfy requests for more detailed measurements.

Rut depth measurements are also stored on floppy disk for later analysis such as plotting or summary reports.

5.2 Rut Depth Plot

Like roadway profiles, rut depth measurements are effectively represented graphically. Software which plots rut depth on the same distance scaling as the profile plots has been written for the pen plotter (Figure 29). Dot matrix routines have not been written, but could be with relatively minor effort.

RUT011: Rut Depth Plot Program

Copyright 1987 SDDOT

Highway: 1083   From 140.00 + 0.00 to 140.00 + 0.10

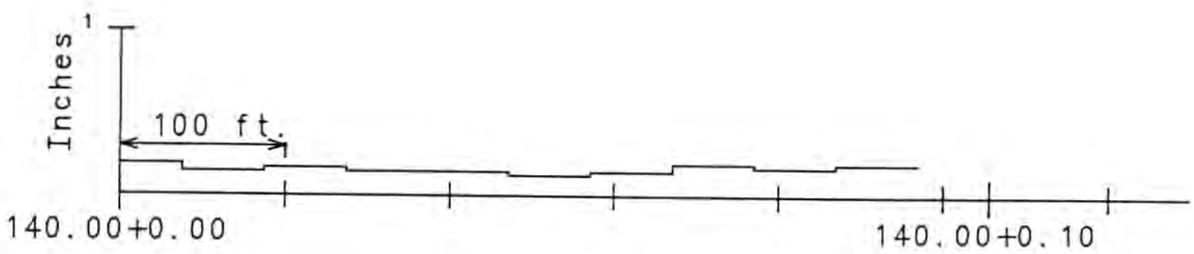


Figure 29: Rut Depth Plot

5.3 Rut Depth Rating

Software to generate a rut depth summary document has also been written. Because it uses only alphanumeric characters (and no graphics), it can be produced on any printer (Figure 30). The document identifies the project location, then displays the minimum, average, and maximum rut depths recorded in each distance interval. The operator may select the beginning and ending of output, as well as the interval at which measurements are to be averaged and displayed. In each interval, asterisks denote the average rut depth and pluses denote plus and minus one standard deviation from the average. Minus signs cover the entire range of measurements in the interval.

```
RUT020: Rut Depth Rating Document                           Copyright 1986 SDDOT
03-APR-89   08:33:25

Highway: 1014                                               Test Vehicle: TBN555
   Lane: 1                                           Average Speed(mph): 55.675
Project: 4-CORNERS TO FT.PIERRE                      Data Interval (ft): 50.000
Remarks: VERY WINDY                                      Resolution(ft):  0.002
   Date: 17-MAY-88                                     # of Data Points:   3891
   Time: 17:20:28

         From     To    Average   Std -------------Rut Depth (inches)------------
  MRM    Disp     Disp   Depth    Dev 0.0        0.5        1.0        1.5      2.0
223.00   0.000    0.091   0.01   0.03  *++-
         0.091    0.182   0.03   0.05  +*++
         0.182    0.273   0.01   0.02  *+-
         0.273    0.364   0.03   0.05  +*++
         0.364    0.455   0.06   0.12  +*+++---
         0.455    0.545   0.31   0.12  ---+++*++
         0.545    0.636   0.09   0.12  ++*+++---
         0.636    0.727   0.33   0.06  |    ++*++
         0.727    0.818   0.26   0.03  |   +*+
         0.818    0.909   0.26   0.07  |   +*++
         0.909    1.000   0.42   0.05  |      +*++
224.00   0.000    0.091   0.45   0.07  |      ++*++
         0.091    0.182   0.33   0.06  |   -++*++
         0.182    0.273   0.37   0.03  |      *++
         0.273    0.364   0.35   0.07  |    ++*++
         0.364    0.455   0.27   0.04  |   +*++
         0.455    0.545   0.24   0.04  |  ++*+
         0.545    0.636   0.28   0.05  |   ++*+
         0.636    0.727   0.27   0.02  |    *+
         0.727    0.818   0.21   0.06  | ++*++
         0.818    0.909   0.30   0.04  |   ++*++
         0.909    1.000   0.29   0.06  |  -++*++

Project Average                   0.24   0.15  -++++*++++--

Disk:  20
File: 014000.690
Operators: SINGH & STEWART
```

Figure 30: Rut Depth Rating Document

5.4 Summary Plots

Another graphical summary of rut depth information is illustrated by Figure 31. The graph shows the percentages of highway length with rut depths falling within certain ranges. Two or more graphs may be compared to show the progression of rutting over time.

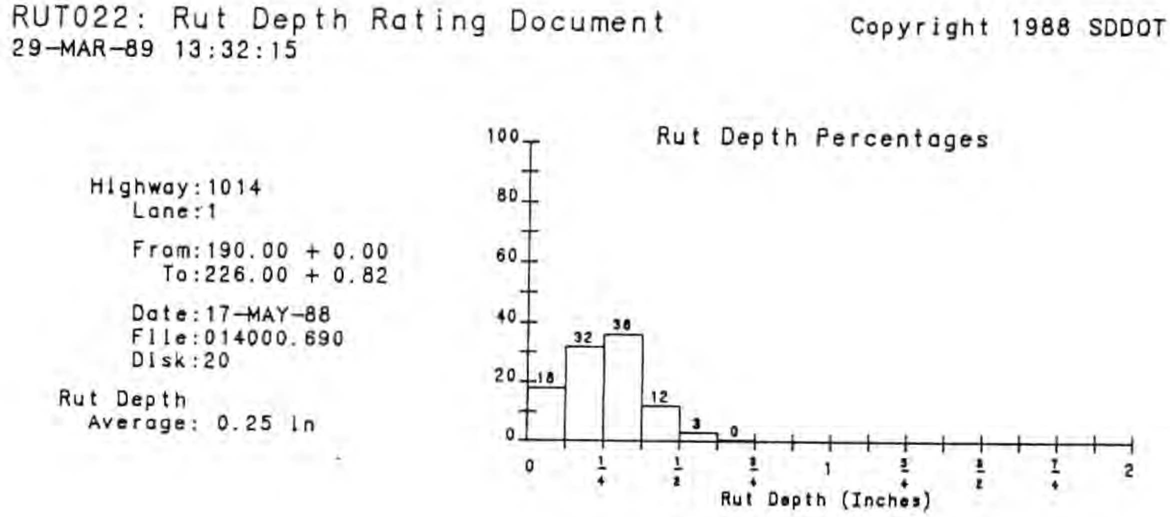


Figure 31: Rut Depth Summary Plot

5.5 Mainframe Interface

Rut depth information can be transferred to a mainframe resident database in a manner similar to roughness ratings. Intervals of specified length, typically one tenth of a mile, are identified by highway name, interval beginning (specified as a Mileage Reference Marker and displacement), and lane. For each interval, average rut depth, maximum rut depth and standard deviation are written to a file (Figure 32). The file can be uploaded via diskette or serial communication lines.

					Rut Depth(in*100)		
Highway		MRM DSP	Date	Lane	Average	Max	Std Dev
1014	B	095000+0000	880531	1	0000	0002	0001
1014	B	095000+0100	880531	1	0007	0019	0007
1014	B	095000+0200	880531	1	0012	0024	0008
1014	B	095000+0300	880531	1	0016	0026	0009
1014	B	095000+0400	880531	1	0005	0014	0005
1014	B	095000+0500	880531	1	0016	0031	0008
1014	B	095000+0600	880531	1	0017	0024	0003
1014	B	095000+0700	880531	1	0008	0024	0009
1014	B	095000+0800	880531	1	0008	0019	0007
1014	B	095000+0900	880531	1	0005	0014	0005
1014	B	096000+0000	880531	1	0010	0014	0004
1014	B	096000+0100	880531	1	0006	0012	0004
1014	B	096000+0200	880531	1	0004	0012	0005
1014	B	096000+0300	880531	1	0007	0010	0002
1014	B	096000+0400	880531	1	0009	0014	0004
1014	B	096000+0500	880531	1	0004	0010	0003
1014	B	096000+0600	880531	1	0004	0019	0007
1014	B	096000+0700	880531	1	0002	0010	0004
1014	B	096000+0800	880531	1	0003	0017	0006
1014	B	096000+0900	880531	1	0006	0014	0004
1014	B	097000+0000	880531	1	0005	0007	0001
1014	B	097000+0099	880531	1	0004	0007	0002
1014	B	097000+0198	880531	1	0005	0007	0002
1014	B	097000+0298	880531	1	0002	0007	0003
1014	B	097000+0397	880531	1	0005	0010	0003
1014	B	097000+0496	880531	1	0001	0002	0001
1014	B	097000+0595	880531	1	0005	0007	0003
1014	B	097000+0694	880531	1	0001	0005	0002

Figure 32: Rut Depth File Format

CHAPTER 6

STATE'S EXPERIENCE

SDDOT has gained considerable experience using the Road Profiler since 1982. Although it is continously being refined, the Road Profiler is no longer experimental, but has become a dependable "production" tool for conducting pavement condition surveys. Its costs, capabilities and limitations are well established.

6.1 Acquisition Costs

Most of the components used to assemble the South Dakota Road Profiler are commercially available, including the van, inverter, computer, terminal, printer, and accelerometer. It is necessary, however, to construct the ultrasonic ranging devices and the electronic boards which interface the ranging devices, accelerometer and transmission sensor to the computer. In addition, some machining of the aluminum sensor beam and assembly of cables is required. A reasonable estimate of hardware costs is $22,000 plus labor which should not exceed $10,000. Software and technical assistance are provided by SDDOT without charge.

Optional equipment can be acquired to make data analysis more convenient. A second computer, costing about $10,000, could analyze data in the office while the test vehicle is in the field and also serve as a spare to the field computer. Another useful option is a pen plotter which allows more versatility and speed in plotting profile and rut depth measurements than does a dot matrix printer. Plotters are available for as little as $2500, depending on the speed and number of pens which are desired. Plotting software is also provided by SDDOT.

Nebraska's experience in replicating the Road Profiler may provide the most realistic estimate of total acquisition cost. During 1987, the Nebraska Department of Roads purchased a van, two computers, instrumentation and spare accelerometers and interface boards. Total cost, including assembly, was just under $50,000.

6.2 Operating Costs

Operating costs of the Road Profiler are reasonable. Based upon South Dakota's experience, the average cost of state-wide surveys is approximately two dollars per mile. This includes vehicle expense, salaries, meals and lodging, supplies, and the costs of transferring roughness ratings, rut depth measurements, and visual ratings to a mainframe database.

These low costs are partially attributable to the experience of SDDOT personnel and the state's predominantly rural highway system, but also result from the fact that measurement and analysis software has been written to match SDDOT's data structures and procedures.

6.3 Traffic Control

In rural settings, traffic control is not normally required. Because the Road Profiler is a standard width vehicle and can operate at all normal speeds, it does not interfere with other traffic.

In urban settings, traffic control is usually not needed. Unless traffic is heavy, the driver can vary the vehicle's speed to negotiate traffic signals and intersections. If heavy traffic or other circumstances would prevent the driver from maintaining a non-stop course, some kind of traffic control may be required.

6.4 Personnel Needs

The Road Profiler is normally operated by a two man crew. During the summer months when the statewide survey is taken, a seasonal employee drives the test vehicle. Most of the equipment operation is performed by a permanent employee to promote consistency in the visual ratings of pavement condition.

Because the measurement software is written to be simple and to require minimal interaction with the operator, single operator operation is possible. For safety considerations, this is only done for short test runs in areas of light traffic.

6.5 Required Training

Field operation of the Road Profiler is relatively straight-forward because the measurement software requires minimal operator intervention. If the operator is familar with the state's highway and reference marker system, a half day's instruction enables him to perform routine operational checks and conduct profile, rut depth and sufficieny surveys.

Additional training is required to perform the various analyses of profile and rut depth measurements. Although the analysis software is easy to operate, it takes time to develop an understanding of what each analysis means and how to manage the large quantities of information represented by the measurements. Basic competency in using the analysis software might be achieved in a week, but full understanding of all the subtleties involved would take much longer.

6.6 Capabilities and Uses

To date, the primary use of the Road Profiler has been to conduct statewide surveys of pavement roughness and rutting. Each year, SDDOT surveys one lane of its entire state highway system and places summary information into its central highway management database.

Recently, engineering applications have begun to be developed. Measured profiles have been used to observe the effects of frost and to estimate quantities of slabjacking required to rehabilitate concrete pavements. Rut depth measurements have been used to estimate the quantities of grinding and/or fill required to eliminate ruts.

The Road Profiler has not been used for construction acceptance. SDDOT uses a profilograph for rigid pavement acceptance because it is used in adjoining states and is familiar to contractors.

6.7 Limitations

As might be expected, the low cost of the Road Profiler contributes to some performance limitations. First, because of inherent limitations in the accuracy of ultrasonic ranging measurements, profile and rut depth accuracy is limited to approximately one sixteenth of an inch (0.005ft). Second, the ultrasonic sensor's maximum measurement rate of one hundred per second restrict the interval at which data may be recorded. At rural highway speeds, the data interval cannot be less than approximately one foot. This limitation results in inadequate sampling of very short wavelengths.

The most significant environmental restriction is that the Road Profiler cannot operate in rain. The ultrasonic ranging sensors, which are open to the air, electrically short if wetted by rain or road spray. Severe winds can also cause invalid ultrasonic range measurements. This problem has occasionally been encountered when the test vehicle encounters winds exceeding 40 mph at certain angles. It appears that the wind interacts with the vehicle or ultrasonic transducers to generate sound which interferes with the measurement.

Early in the Road Profiler's development, measurements were affected by extreme surface textures, particularly chip seals with large aggregates. Improvements made to the ultrasonic ranging devices in 1986 essentially eliminated effects to computed Present Serviceability Indexes. PSIs show very little effect from chip seals, open graded asphalts, or concrete tining. Measurements have even been successful on gravel roads.

The effect of coarse texture may be greater on International Roughness Indexes, however. During a demonstration at Fort Collins, Colorado in 1987, profiles were significantly affected by heavy tining (2). Although the Road Profiler was able to profile the very heavily tined concrete test section, the computed roughness ratings were too high. This result was unexpected because that type of tining had not been encountered before. It is not known whether the tining or a heavy layer of dust on the pavement affected the measurements.

---

(2) Donnelly, D.E., Hutter, W., and Kiljan, J.P., "Pavement Profile Smoothness Seminar Proceedings", U.S. Department of Transportation, Federal Highway Administration, FHWA-DP-88-072-003,4,5, 1988.

Since the Ft. Collins meeting, revisions have been made to the method of IRI computation. Specifically, very long wavelengths present in the recorded profiles were found to contribute up to 0.2 mm/km to computed IRIs, especially at the beginning of profiles. Prefiltering the profile to attenuate wavelengths longer than 200 feet substantially eliminates this effect. Likewise, the ultrasonic ranging device's 0.005 foot (.06 inch) accuracy limitation also increases the IRI. Prefiltering the profile to attenuate wavelengths shorter than 2.5 feet improves the Road Profiler's estimate of IRI. Still, some variation of IRI with surface texture was noted during the performance evaluation for this report.

Finally, one limitation may be particularly important in urban areas. The Road Profiler should not be stopped while measuring profiles because accelerations and deccelerations often cause the vehicle to pitch significantly. During these periods, the accelerometer is not vertical and does not sense vehicle motions accurately. The measured profile then contains errors which can be interpreted as severe roughness. In South Dakota, stops can almost always be avoided, but the situation might be different in other parts of the country.

6.8 Manufacturer Support

"Manufacturer support" is difficult to evaluate because the Road Profiler was constructed in house. In house manufacture can be an advantage or disadvantage, depending upon the capabilities of the operating agency. If the agency possesses sufficient technical expertise, an in house system will usually be well understood and more easily modified and maintained than a purchased system. If such expertise is not available, maintenance becomes difficult or impossible.

SDDOT has provided support to other agencies who have decided to duplicate the Road Profiler by providing equipment specifications, schematic diagrams, technical advise and software. Assistance in final assembly, system initialization and checkout have been provided at SDDOT offices in Pierre, SD. To date, no charges have been made for any of these services.

6.9 Vehicle Modifications

A few modifications to the standard Ford van are required to support the Road Profiler instrumentation. First, the front bumper is replaced by a 9x4x81" aluminum channel to which the accelerometer and ultrasonic ranging devices are attached. Second, a 500 watt sine wave inverter installed beneath the rear seat supplies high quality 115vac to the computer. Finally, the van is equipped with a high capacity alternator to supply sufficient power to the inverter.

6.10 Equipment Reliability and Durability

The Road Profiler has proved to be a reliable piece of equipment for high mileage, long duration surveys. The only components which require routine maintenance are the ultrasonic ranging transducers, which must be replaced if they become contaminated by water-borne dirt. On average, each transducer will be replaced once or twice per year, at a cost of less than $20 apiece.

Electronic equipment repair is occasionally required. During the six years in which SDDOT's original computer was used, it required replacement of one floppy disk drive and repair to its power supply. The computer was replaced during the summer of 1987. The sine wave inverter has twice required replacement of a power transistor.

6.11 Effects of Vehicle Loading

Because the Road Profiler measures profile rather than vehicle response to profile, measurements are not influenced by vehicle loading.

6.12 Productivity

In statewide survey use, the Road Profiler has demonstrated high productivity rates. SDDOT performs its 8500 mile annual survey in approximately eleven weeks of four ten-hour days. On average, approximately three to four hundred miles are driven daily, of which nearly two hundred are tested.

After the field survey is complete, another two or three man-weeks are required to compute roughness ratings and transfer roughness, rut depth and visual rating information into SDDOT's central database.

CHAPTER 7

PERFORMANCE EVALUATION

In the spring of 1987, field tests were conducted to determine the quality of profile and rut depth measurements attainable by the South Dakota Road Profiler. Measurements obtained by the Road Profiler were compared to those taken manually, and various analyses were performed to evaluate the agreement between manual and automated measurements.

7.1 Site Selection

For convenience, ten test sections were selected in the area surrounding Pierre (Figure 33). Sections of various roughness and rut depth were chosen for each general pavement type--portland cement concrete, smooth textured asphalt concrete, and coarse textured (chip sealed) asphalt concrete. Most of the sections were within ten miles of Pierre, but the most distant was thirty-five miles away. The locations of the test sites are listed in Table 1.

Each section was 1024 feet, slightly less than 0.2 miles, long. This length was judged to be long enough to provide good measurements, but short enough to accomplish the manual surveys with available manpower. The exact length was chosen because it is a power of two, and therefore slightly more convenient for spectral analysis.

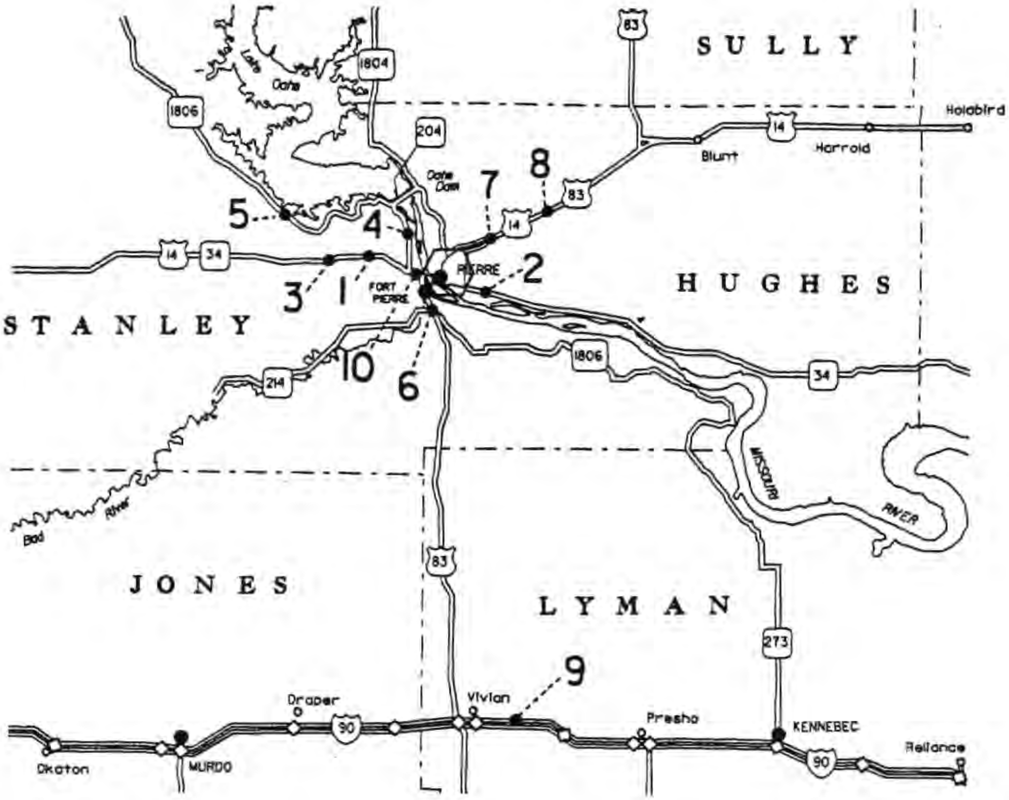


Figure 33: Test Section Locations

Table 1: Verification Site Locations

Site	Highway	MRM	Surface Type	Rut Depth
1	US14	222	Smooth bituminous	0.5"
2	SD34	214	Medium chip seal	0.8"
3	US14	219	Smooth bituminous	0.2"
4	SD1806	188	Medium chip seal	0.3"
5	SD1806	203	Coarse chip seal	0.4"
6	US83	117	Chip seal	0.3"
7	US14	233	Tined PCC	<0.1"
8	US14	238	Tined PCC	<0.1"
9	I90	218	Continuously reinforced PCC	0.1"
10	US14	227	Rough bituminous	0.3"

7.2 Manual Survey Method

Manual profile and rut depth surveys were taken on every test section. Grids were painted on the pavements for reference (Figure 34). Grid lines were spaced at ten foot intervals longitudinally, except for a four foot segment at the section end. Grid lines were positioned transversely to match the Road Profiler's sensor spacing and the observed locations of wheel rut.

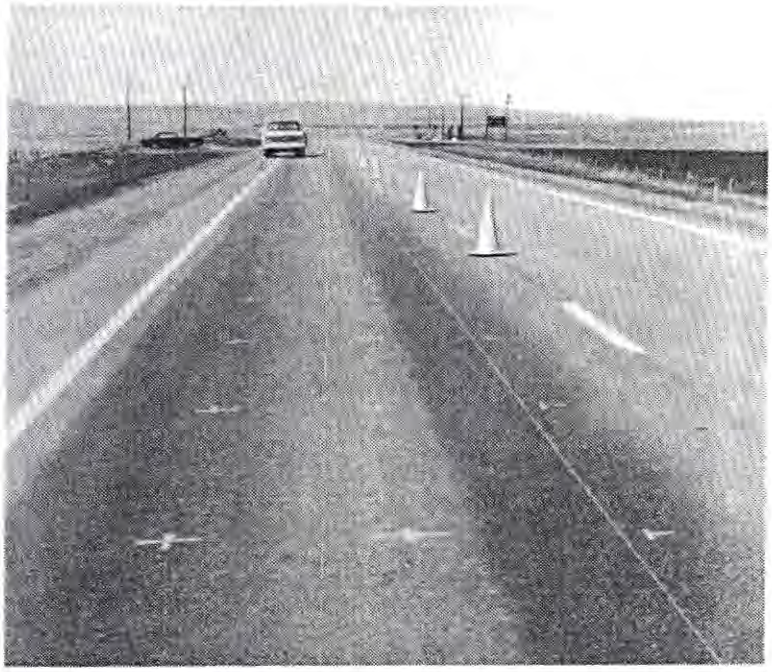


Figure 34: Test Site Survey Grid

The survey was performed using a modified rod and level method. Specifically, rod and level were used to determine the elevations of the grid points with an estimated accuracy of 0.002 feet. Rut depths were computed directly from the rod and level measurements at the grid points. No other rut depth measurements were made.

Profile measurements between the grid points were taken using an E. L. Face "Dipstick", an instrument which has previously found use in measuring concrete floor flatness. The Dipstick (Figure 35) consists of an inclinometer enclosed in a case supported by two feet spaced precisely twelve inches apart. Internal electronics converts the measured inclination angle into a measurement of elevation difference at the feet. Elevation differences are recorded sequentially by pivoting the Dipstick on one foot, in effect flip-flopping the instrument down the profile survey line. Profiles are computed by sequentially summing elevation differences over the section length.

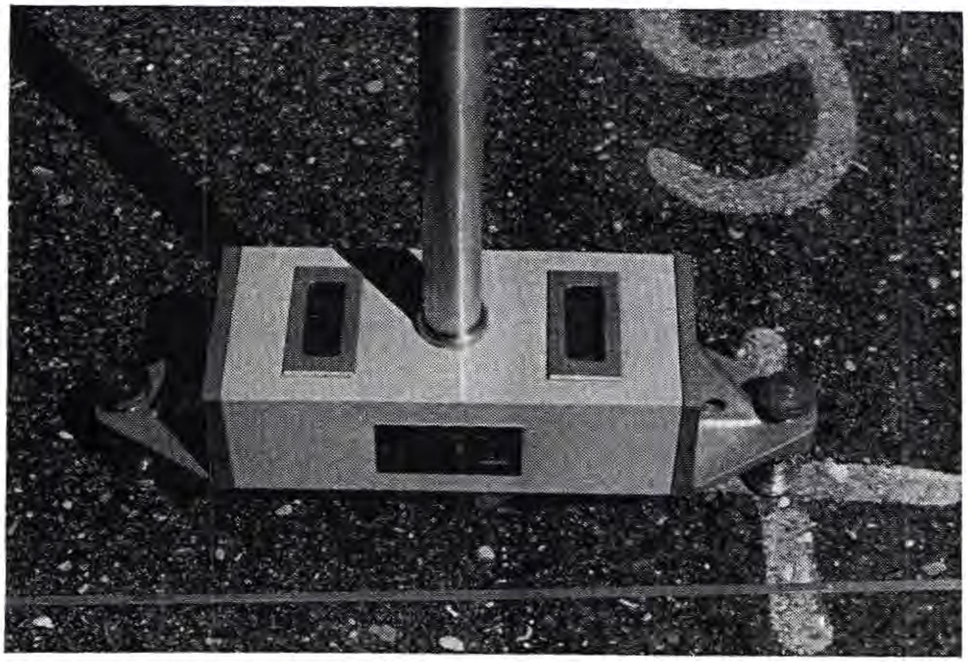


Figure 35: E.W. Face "Dipstick"

Although the Dipstick can provide elevation difference measurements accurate to five thousandths of an inch, two factors limit its accuracy for pavement profile measurement. First, the feet provided with the instrument were mettallic and pointed. They worked reasonably well on portland cement concrete surfaces, but performed poorly on asphalt pavements. The feet tended to slide off rock in the pavement while the Dipstick was being rotated, resulting in a loss of profile continuity. This problem was circumvented by replacing the standard feet with pivoting, flat-bottomed, rubber padded feet. With practice, operators were able to step through the profile surveys, maintaining very good longitudinal distance accuracy.

The second factor limiting the profile accuracy is that small errors in individual elevation difference measurements accumulate as the differences are summed, resulting in a slight drift away from the true profile. The drift, usually less than 0.0005 feet per feet, can be corrected by combining Dipstick measurements with rod and level measurements, in effect forcing the Dipstick profile (measured at one foot intervals) to pass through the rod and level profile (measured at ten foot intervals). For the ten sites surveyed, the correction over the total site length never exceeded 0.2 feet.

Manual profile surveys were only recorded for the left wheelpath, the wheelpath surveyed by the Road Profiler.

7.3 Road Profiler Survey Method

The Road Profiler measured profile and rut depths six times at each test site. Two runs were made at nominal speeds of 25, 40 and 55 mph so effects of speed could be observed.

For the 40 and 55 mph runs, profiles were recorded at intervals of one foot. Profiles were recorded at one-half foot intervals for the 25 mph runs. In all cases, rut depths were recorded at every other profile point.

7.4 Analysis Methods

Profiles measured by the Road Profiler were compared to manually surveyed profiles several ways. First, profiles were plotted with cutoff wavelengths of one thousand feet and two hundred feet for direct visual comparison. Long wavelength plots illustrate the Road Profiler's ability to measure wavelengths up to a few hundred feet in length. In some cases, the distortion of longer wavelength features is evident.

The plots with two hundred foot cutoff wavelength better illustrate short features which contribute to pavement roughness. They permit plotting at a larger scale, so details which affect computation of PSI and IRI can be observed.

Slope power spectral density plots were generated for the manually surveyed profile and one profile measured by the Road Profiler at each test speed. They represent the actual spectral content of the profiles as they were recorded. No additional filtering was performed prior to the spectral analysis.

IRI and PSI ratings were computed for the manually surveyed profile and for all profiles recorded by the Road Profiler. Present Serviceability Indexes are considered important to SDDOT, but International Roughness Indexes are of greater interest to other agencies.

Rut depths were plotted for the manual survey and for one Road Profiler survey made at each of the test speeds. Average rut depths were computed to determine whether bias existed in the measurements. Standard deviations were computed to determine whether Road Profiler measurements were more variable than the manual survey.

7.5 Roughness Measurement Evaluation

While detailed profile and roughness measurements are presented for each site in the following chapter, the overall evaluation will concentrate on comparisons between roughness indexes. Figure 36 plots the International Roughness Indexes obtained from Road Profiler measurements against those obtained from manual survey. Figure 37 similarly plots Present Serviceability Indexes. Data are labeled according to speed and test site number. The line representing a linear regression of all Road Profiler indexes against manual survey indexes is also plotted.

For the International Roughness Index, the regression equation is

$$IRI_{Road\ Profiler} = 0.96\ IRI_{Survey} + 0.14 \tag{17}$$

with R^2=0.98. That is, IRIs measured by the Road Profiler in this evaluation tend to be approximately 0.1 mm/m higher than those measured by manual survey, especially at low IRI values. Several factors contribute to this trend.

On jointed concrete pavements (Sites 7-8), the profiles obtained by the Road Profiler show stronger features corresponding to joint spacing. The IRIs obtained by the Road Profiler are correspondingly higher. More recent profiles on this highway indicate that the pavements' profiles change with variations in pavement temperature. Within days, slab faulting and curl appear and disappear. Because the manual survey and Road Profiler measurements were taken about ten days apart, it is believed that this phenomenon contributed to the profile differences seen in this investigation, but it was not possible to verify this hypotheses.

Some of the profiles measured on the continuously reinforced concrete pavement (Site 9) also show marked differences at specific wavelengths, namely the spacing of transverse reinforcing steel. One explanation is that some profiles' sampling intervals coincide with the location of reinforcing bars; these profiles might emphasize the four foot

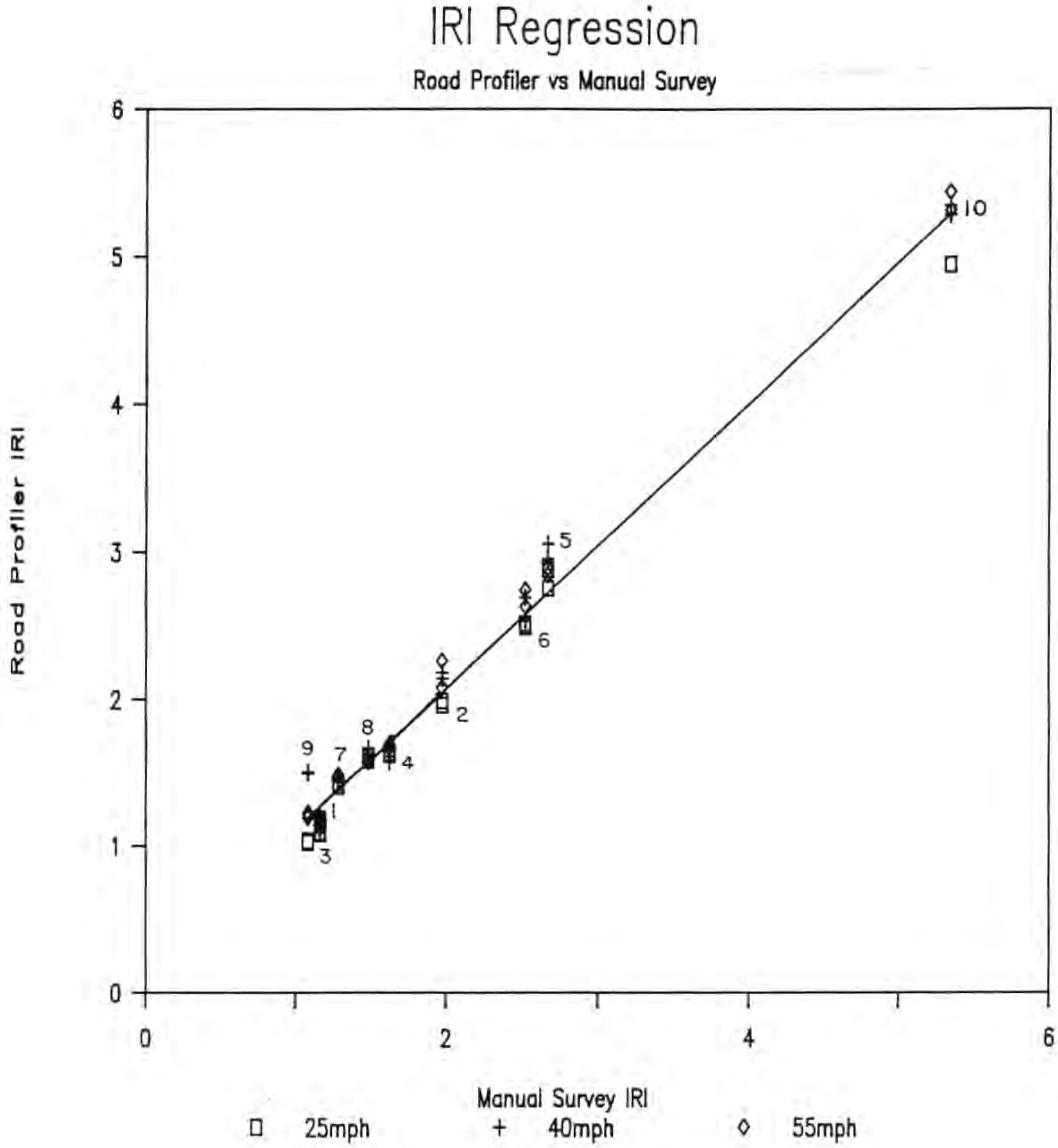


Figure 36: IRI Comparisons

wavelength corresponding to the transverse cracking pattern. This wavelength might be less evident if data were recorded between the cracks.

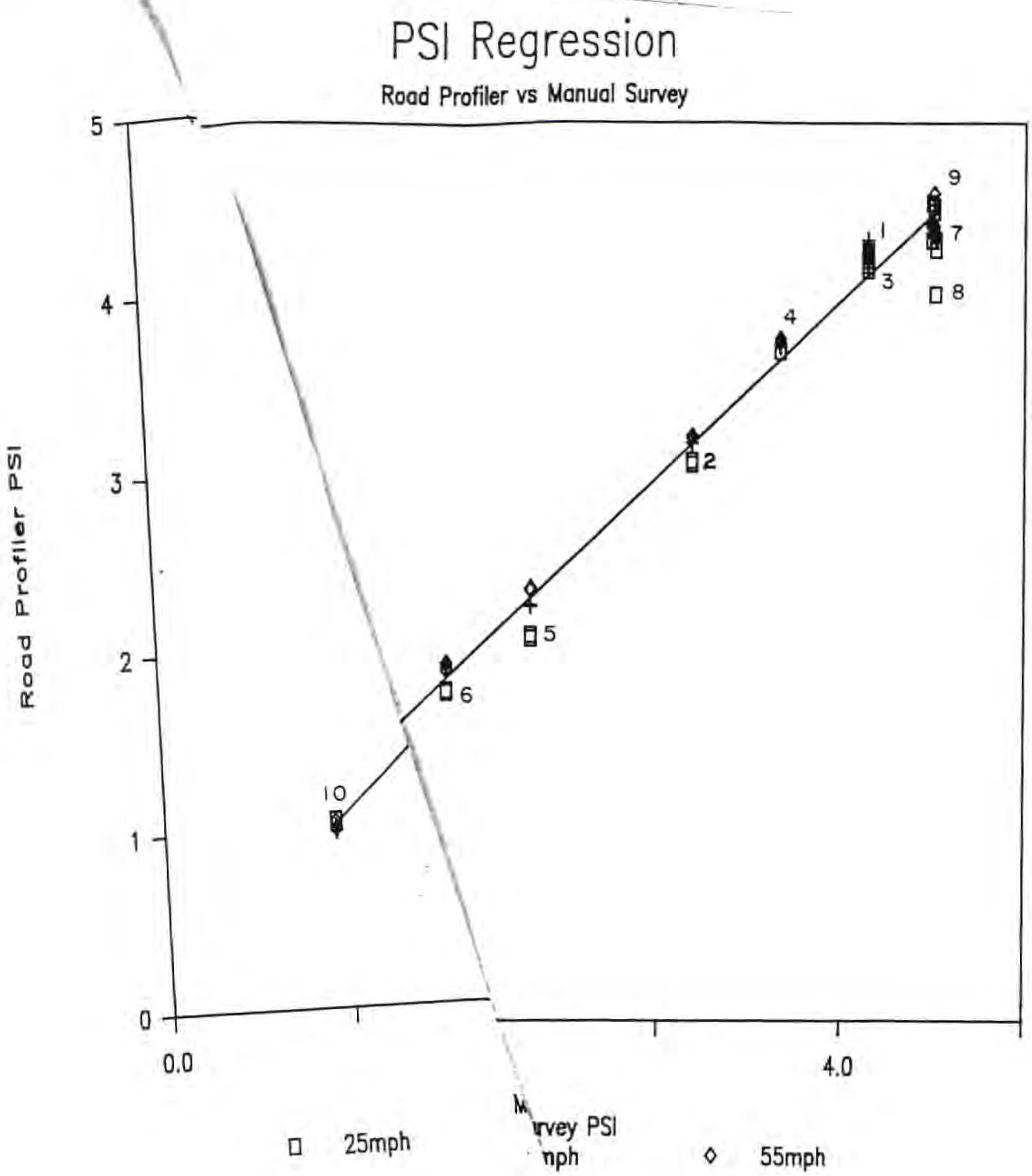


Figure 37: PSI Comparisons

IRIs obtained by the Road Profiler tend to be somewhat higher than the manually surveyed IRIs on coarse textured pavements (Sites 2, 5 and 6). In these cases, power spectral density plots show higher content of wavelengths shorter than five feet. Although the Road Profiler profiles were filtered to attenuate wavelengths shorter than 2.5 feet, IRIs still exceeded the manual survey IRI by up to 0.2 mm/m. It is not known whether other filtering techniques might produce better agreement.

Where coarse texture appears to be a factor, IRIs tend to increase with increased vehicle speed. This is consistent with the idea that a weak, scattered echo would be harder to detect at higher speeds, because the transducer moves farther between sound transmission and echo detection. Variations between different speeds' IRIs exceed 0.2 mm/m on the coarsest pavements.

Generally, there is less variation between the Present Serviceability Indexes computed for manual surveys and Road Profiler. The regression equation is

$$PSI_{Road\ Profiler} = 0.98\ PSI_{Survey} + 0.12 \quad (18)$$

with $R^2=0.99$. Differences between PSIs measured at different speeds are also smaller. These effects result because the PSI is less sensitive to short wavelengths than is the IRI.

In summary, roughness ratings generated by the Road Profiler show general agreement with those obtained by the rod, level and Dipstick survey. The measurements made for this study appear to show some effects from pavement behavior, sampling interval, and coarse pavements, however.

7.6 Rut Depth Measurement Evaluation

Rut depths measured by the Road Profiler show excellent agreement with those obtained by manual survey. The relationship between the measured average depths (in inches) is shown by Figure 38 and given by the equation

$$RUT_{Road\ Profiler} = 0.99\ RUT_{Survey} + 0.02 \quad (19)$$

with $R^2=0.99$. Although no regression is presented for standard deviations in rut depth, agreement is also excellent.

The average rut depth measured by the Road Profiler is significantly higher than the manually surveyed value at only two sites (Sites 5 and 10). These pavements are the most distorted because of subgrade weakness and heavy traffic. At both sites, all Road Profiler measurements are consistent with each other. At Site 4, the Road Profiler's

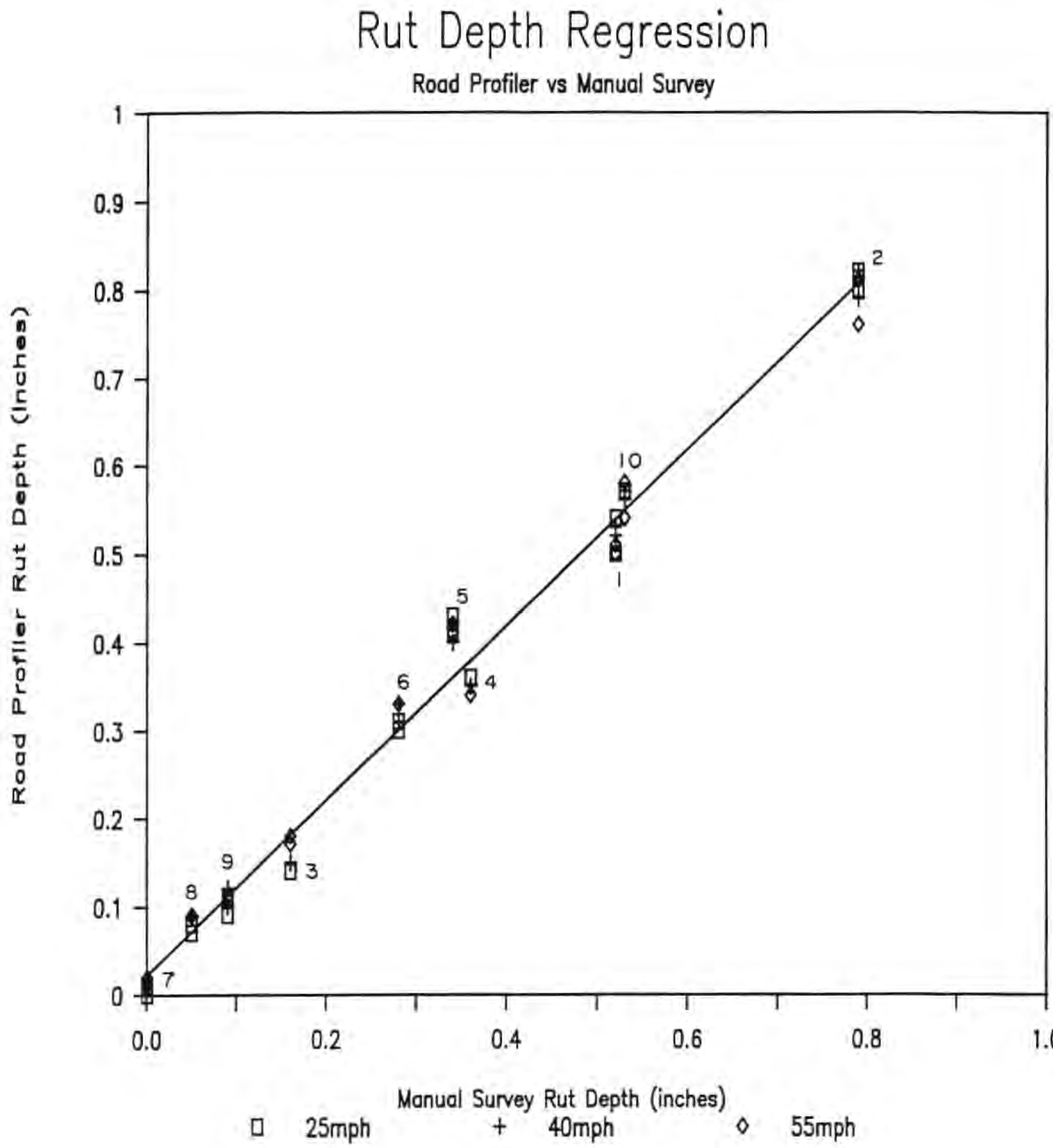


Figure 38: Rut Depth Comparisons

average rut depth is smaller than the manual survey's. Even so, the difference is not much greater than the inherent variability among measurements.

The standard error between manual survey and Road Profiler rut depth measurements is approximately 0.03 inches. This value is good considering the relatively short test section length, and is certainly acceptable for most applications. It should be noted, however, that the agreement between Road Profiler and manual survey measurements partly results from the method used to perform the manual survey. Manual survey rut depths were computed from elevations taken in the same paths that the Road Profiler tracked. A comparison to stringline or straightedge measurements might have produced different results, especially on distorted pavements.

7.7 Operational Evaluation

No operational problems were encountered during the course of this evaluation.

SITE DATA

CHAPTER 8

SITE DATA

This chapter provides descriptions and photographs of each of the ten test sites. Profiles, power spectral density plots, and roughness ratings bar charts are presented for each site, along with rut depth plots and rut depth bar charts.

8.1 Site 1

Site 1 is on US14 approximately five miles west of Pierre (Figure 39). The highway was constructed in 1984. By 1987, excess asphalt in its 6" bituminous mat had contributed to rutting and flushing in the wheelpaths. Heavy truck traffic into Pierre had aggravated the rutting problem until double ruts, corresponding to truck dual tire spacing, were common. The pavement's texture was smooth (Figure 40).

The profile measurements obtained by the Road Profiler agree well with the manual survey, as shown by the plots at 1000' and 200' cutoff wavelengths (Figures 41 and 42). The Road Profiler profiles show higher content of wavelengths shorter than 5', but agree well with the manual survey at longer wavelengths (Figure 43).

Roughness ratings measured by the Road Profiler are close to those obtained from the manual survey (Figure 44). The measured Present Serviceability Indexes, which range from 4.24 to 4.35, are slightly better than the surveyed PSI of 4.14. Measured International Roughness Indexes range from 1.11 to 1.19, compared to the surveyed IRI of 1.16.

Rut depth measurements also agree well (Figure 45). The average rut depth for every run of the Road Profiler is within 0.02 inches of the 0.52 inch average obtained from manual survey. The computed standard deviations and rut depth plots (Figure 46) are consistent with each other.

Figure 39: Site 1

Figure 40: Site 1 Pavement Texture

SITE DATA
Site 1

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 1
Highway: 1014 From 222.00 -0.19 to 222.00 + 0.00
Cutoff Wavelength = 1000ft

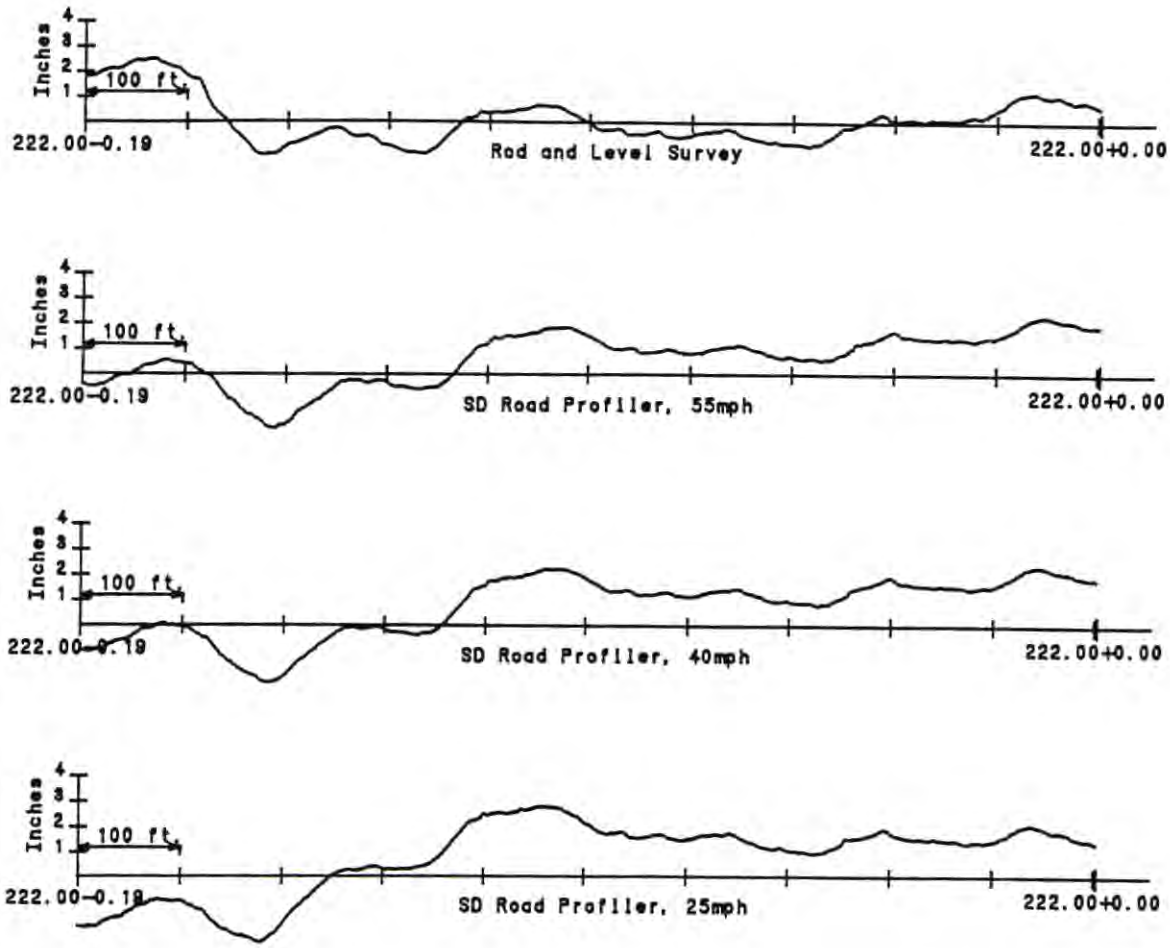


Figure 41: Site 1 Profiles, 1000' Cutoff

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 1
Highway: 1014 From 222.00 −0.19 to 222.00 + 0.00
Cutoff Wavelength = 200ft

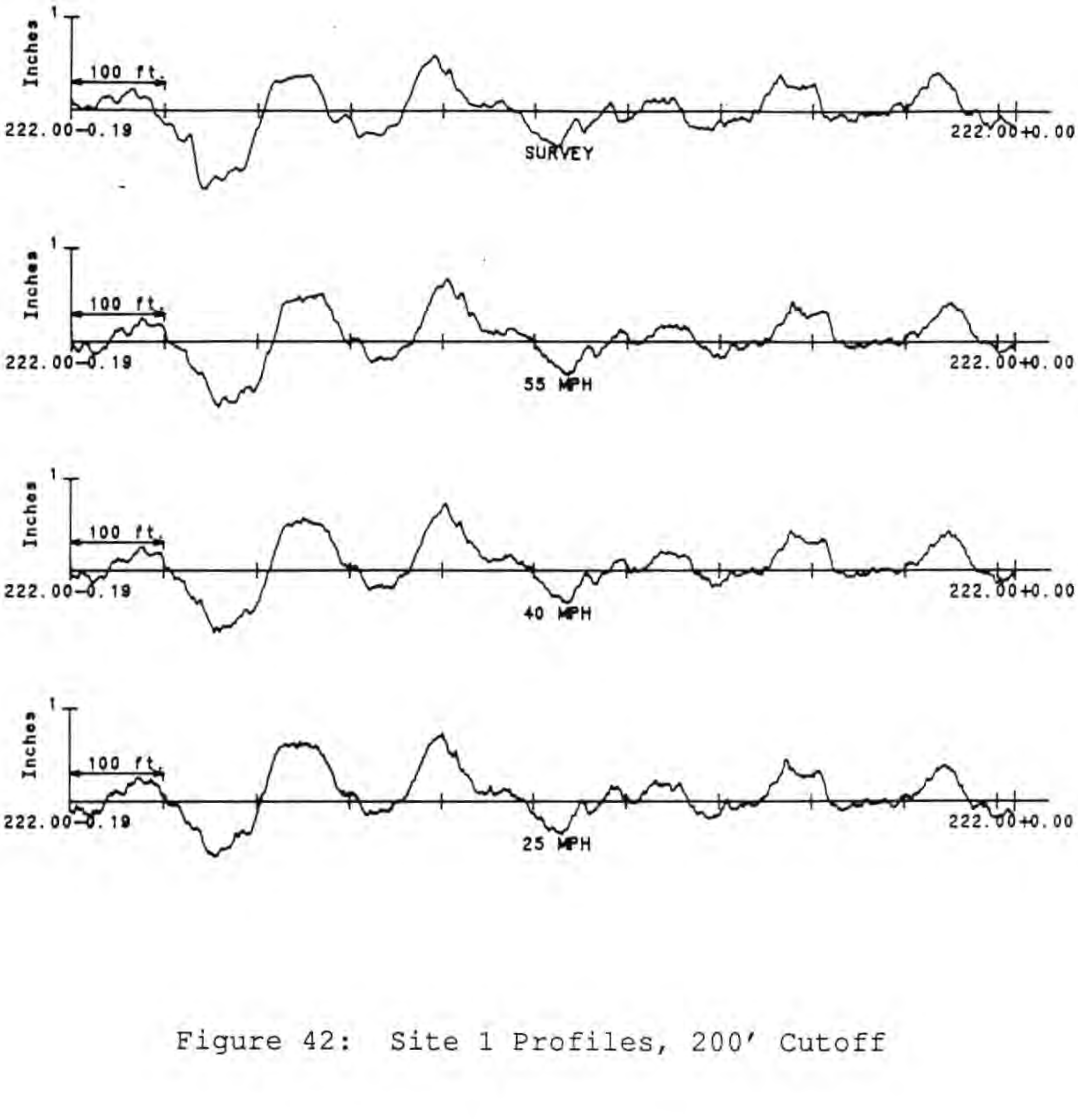


Figure 42: Site 1 Profiles, 200′ Cutoff

SITE DATA
Site 1

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site #1
Highway: 1014   From 222.00 -0.19 to 222.00 + 0.00

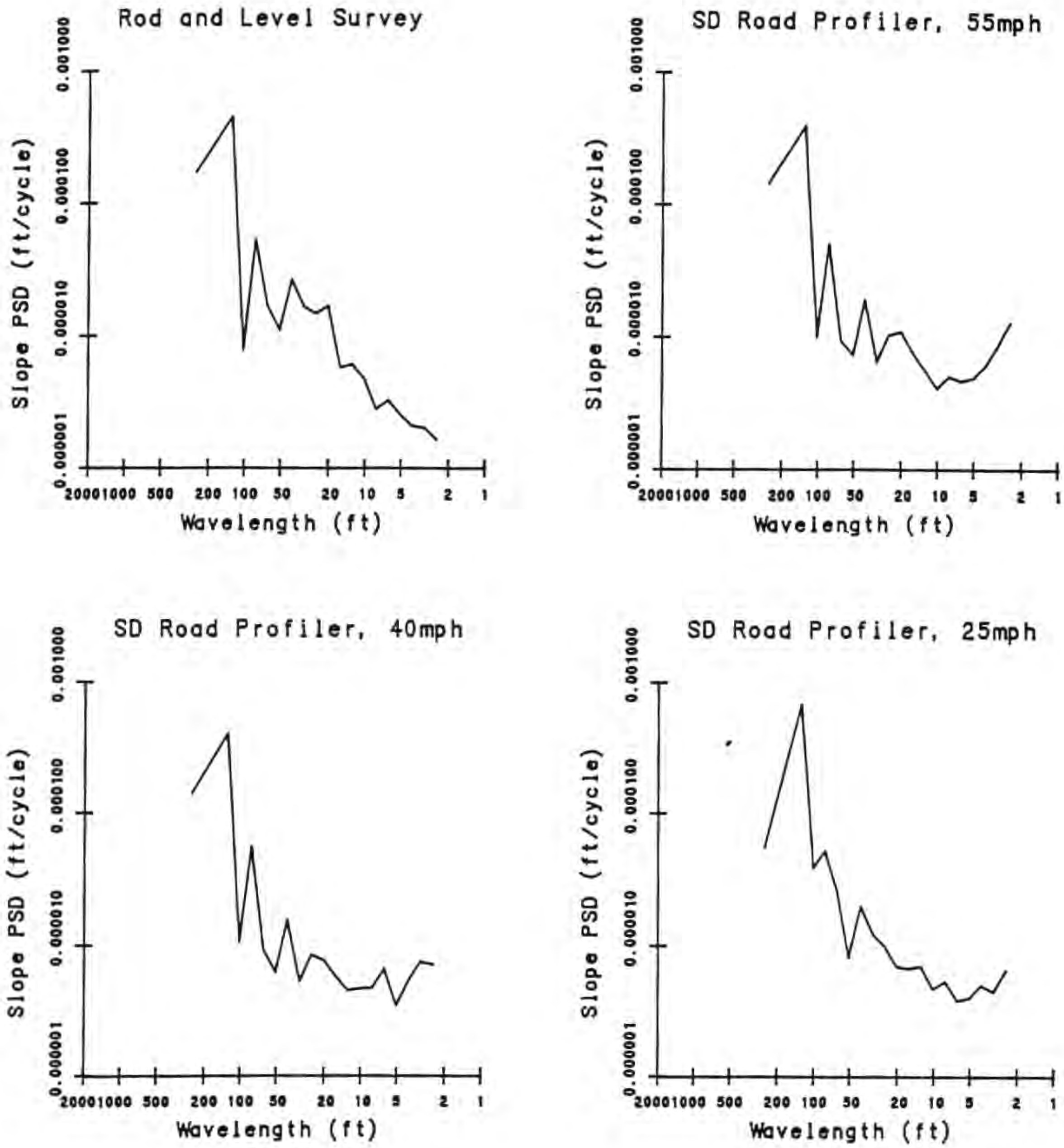


Figure 43: Site 1 Spectral Analysis Plots

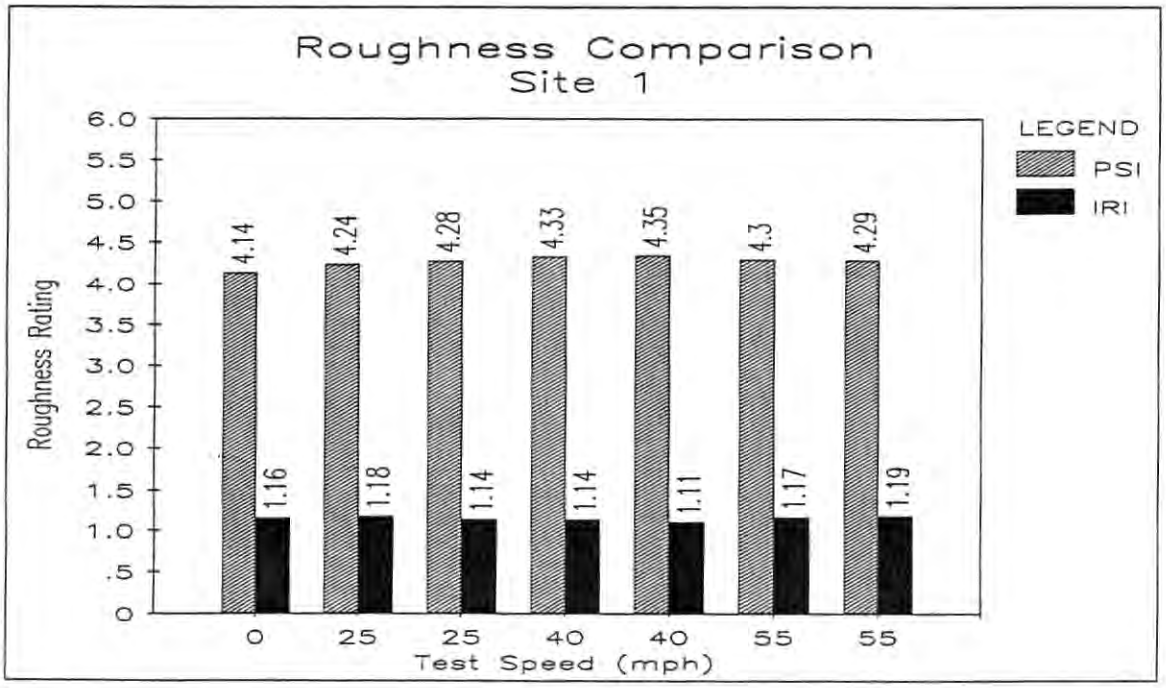


Figure 44: Site 1 Roughness Ratings

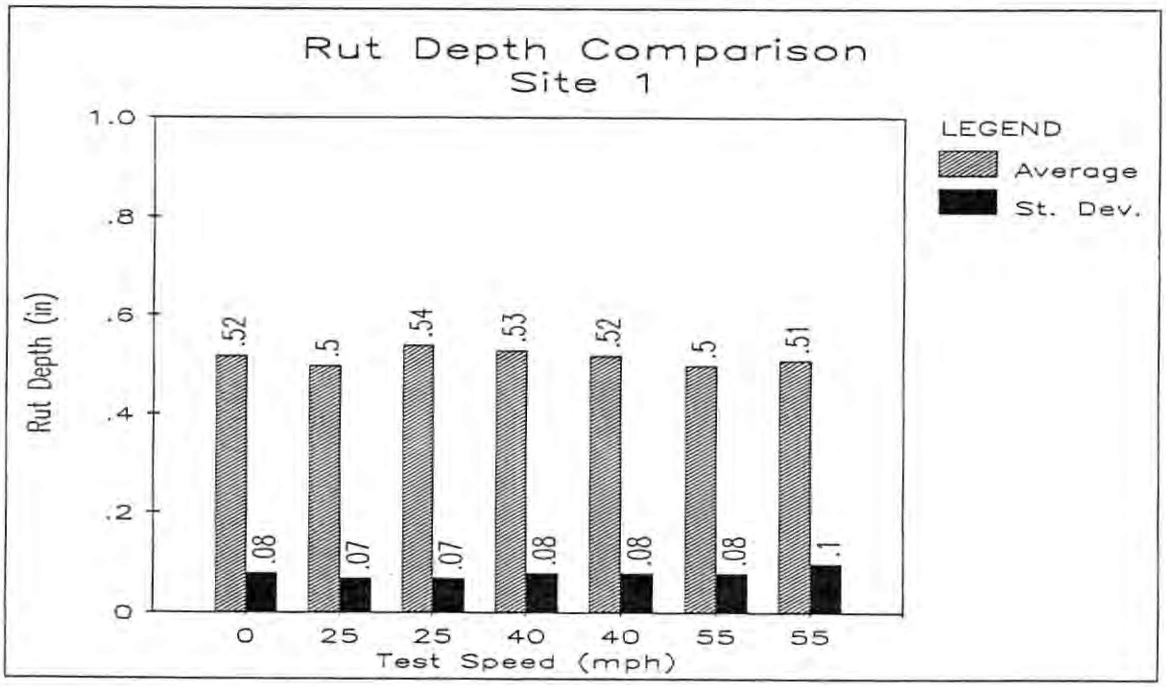


Figure 45: Site 1 Rut Depth Averages

SITE DATA
Site 1

RUT012: Rut Depth Plot Program

Demonstration Project 72; Site # 1
Highway: 1014 From 222.00 -0.19 to 222.00 + 0.00

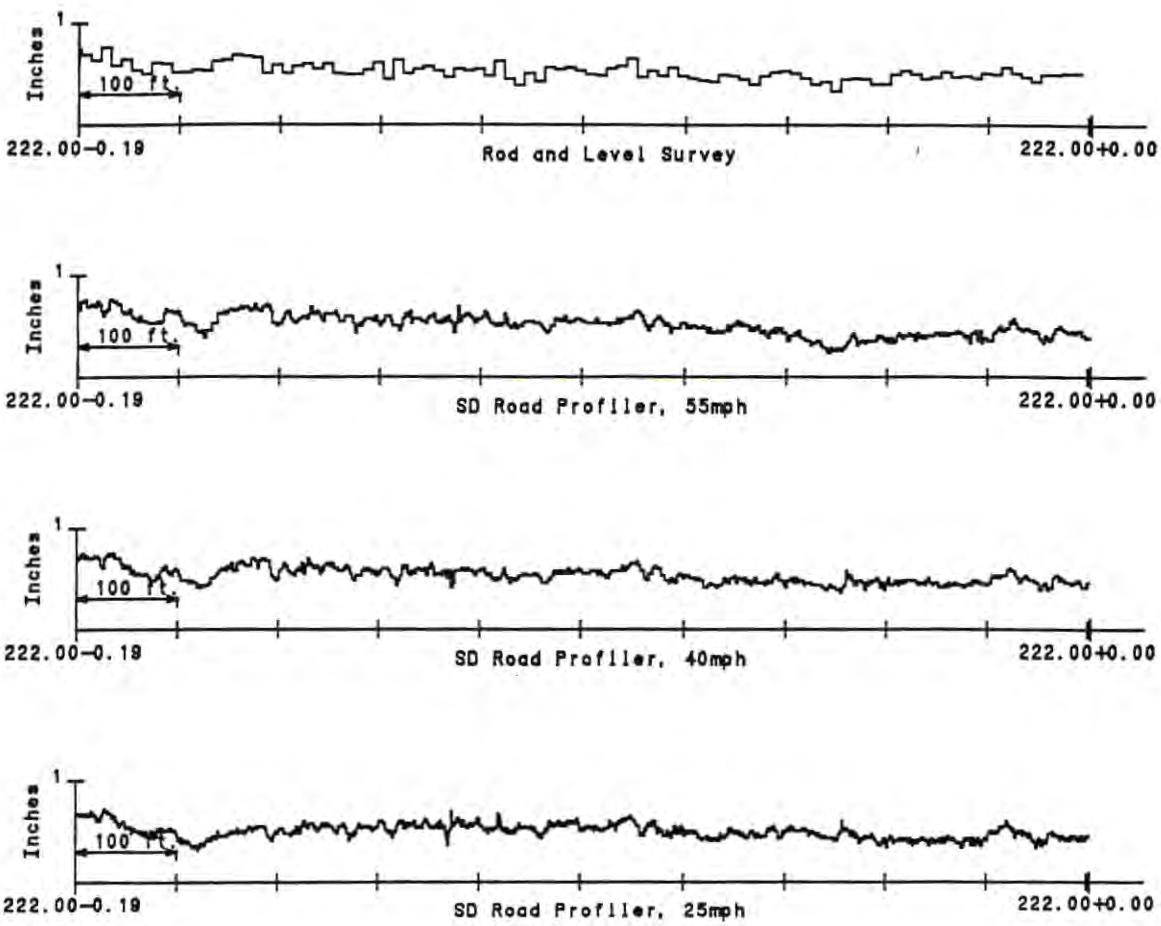


Figure 46: Site 1 Rut Depth Plots

8.2 Site 2

Site 2 is on SD34, approximately four miles east of Pierre (Figure 47). It was constructed in 1955, and had received no major improvements prior to these tests. Its pavement, 1.5" of asphalt over 5" of asphalt treated base, exhibited moderate roughness. Rut depths ranged from 0.5" to 1.2". A maintenance chip seal gave the pavement coarse texture (Figure 48).

Profile measurements taken by the Road Profiler agree well with the manual survey for long wavelengths (Figure 49), but show very short wavelength features not present in the manual survey (Figure 50). The power spectral density plots likewise show agreement at long wavelengths; the measured profiles have a higher content of wavelengths under five feet than does the manually surveyed profile (Figure 51). Presumably, these differences represent effects of coarse pavement texture. (The 25 mph profile appears to be most affected, but this is somewhat misleading. Because the 25 mph profile was sampled at one-half foot intervals, random one-sixteenth inch variations are simply more frequent than in the other profiles, which were measured at one foot intervals.)

The higher short wavelength content is reflected in the International Roughness Indexes (Figure 52). The IRIs obtained from the 40 and 55 mph profiles are approximately 0.2 mm/m higher than that obtained from the manual survey. Only the 25 mph IRIs are close to the manual survey IRI. The computed PSIs show less variation. The PSIs of the measured profiles are all within 0.08 of the manual surveyed profile's PSI.

The Road Profiler's rut depth measurements agree well with those obtained by manual survey (Figure 53). All of the Road Profiler's average rut depths are within 0.03 inches of the manual survey average of 0.76 inches. The standard deviations are also nearly identical. There is also good visual agreement in the plotted rut depths (Figure 54).

Figure 47: Site 2

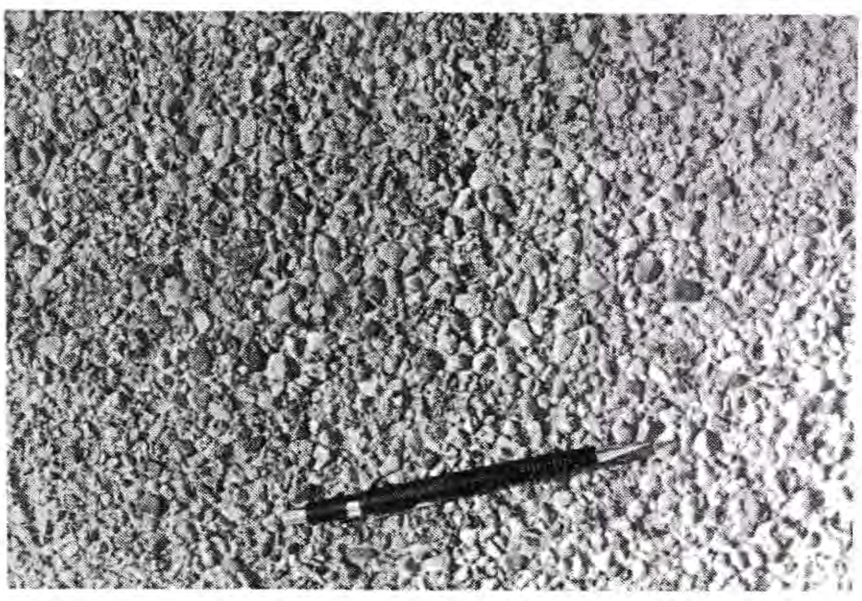


Figure 48: Site 2 Pavement Texture

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 2
Highway: 1034 From 214.00 + 0.00 to 214.00 + 0.19
Cutoff Wavelength = 1000ft

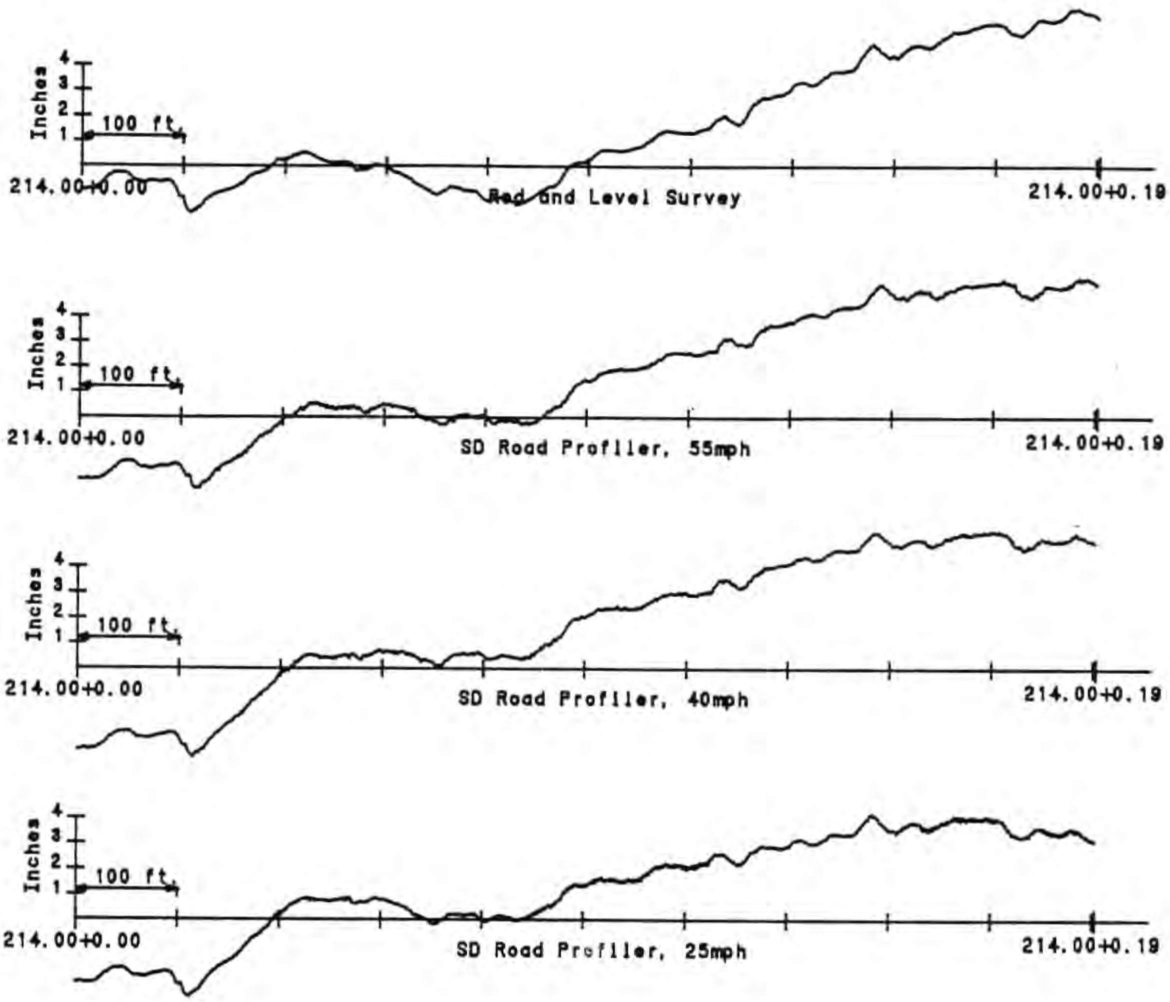


Figure 49: Site 2 Profiles, 1000′ Cutoff

SITE DATA
Site 2

PRF012: Filtered Profile Plot Program
Copyright 1987 SDDOT

Demonstration Project 72; Site # 2
Highway: 1034 From 214.00 + 0.00 to 214.00 + 0.19
Cutoff Wavelength = 200ft

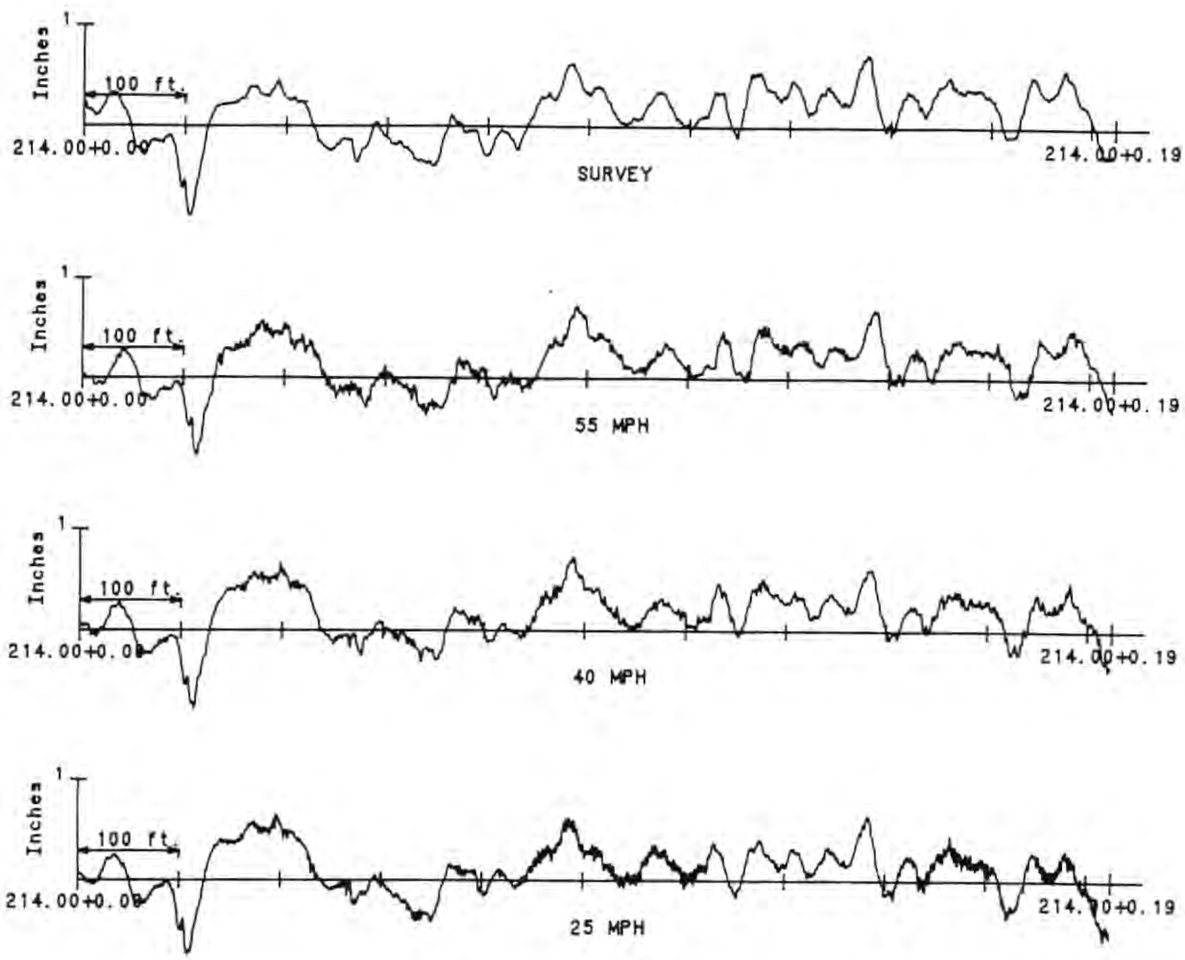


Figure 50: Site 2 Profiles, 200' Cutoff

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site #2
Highway: 1034   From 214.00 + 0.00 to 214.00 + 0.19

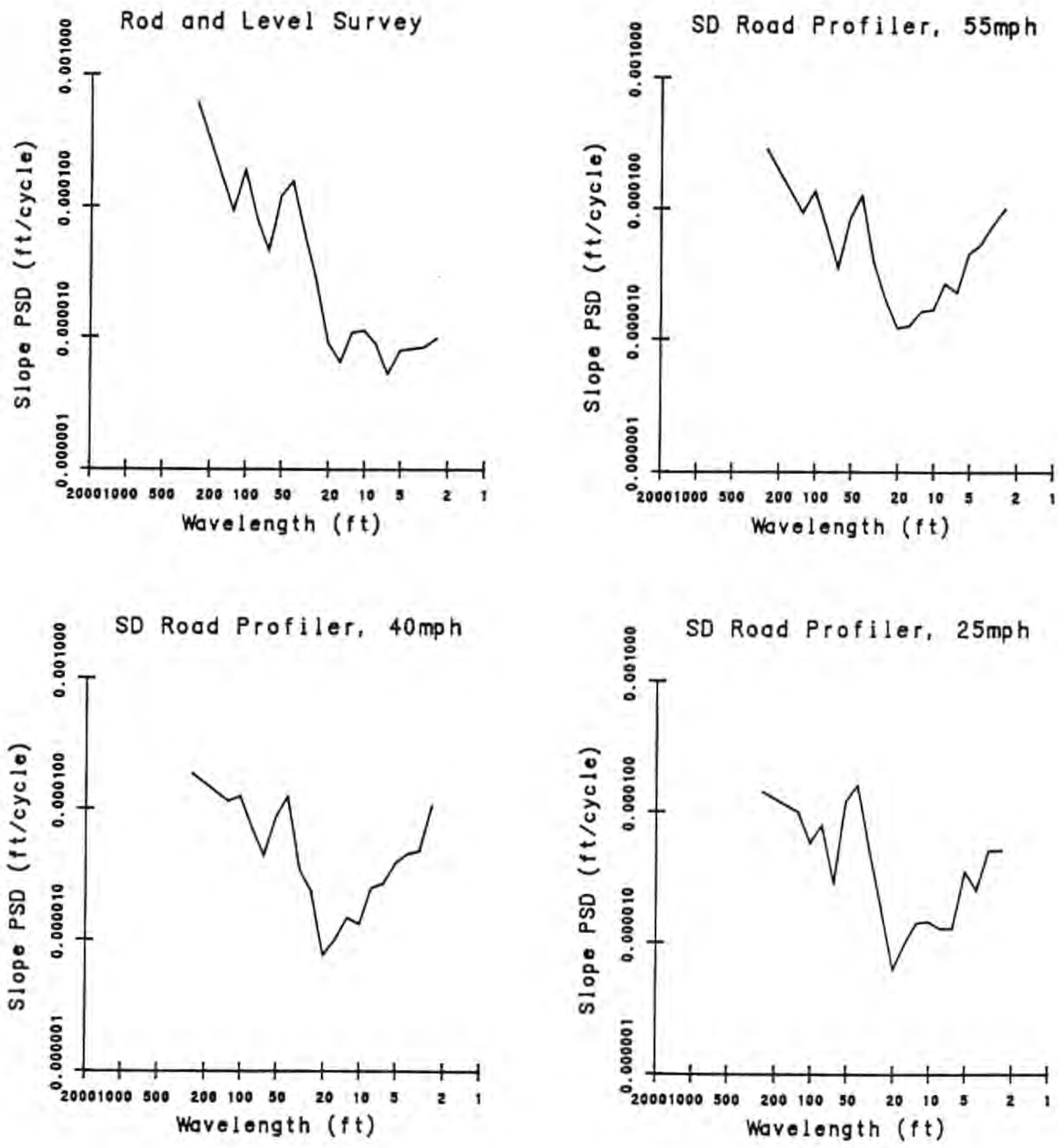


Figure 51: Site 2 Spectral Analysis Plots

SITE DATA
Site 2

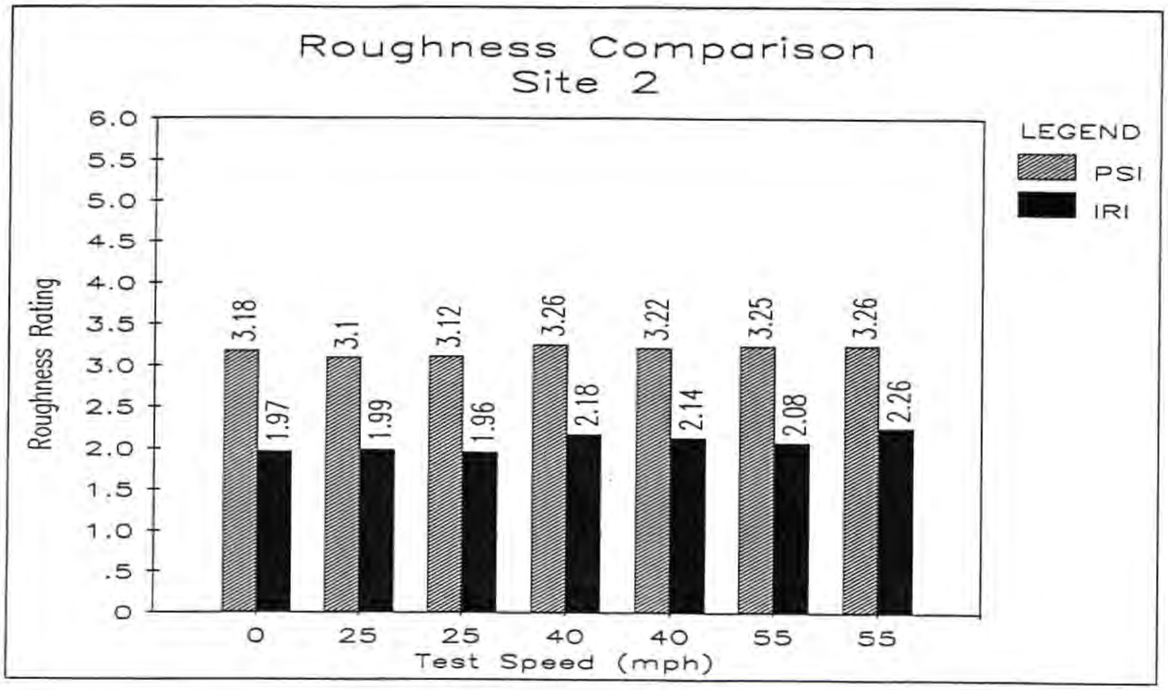


Figure 52: Site 2 Roughness Ratings

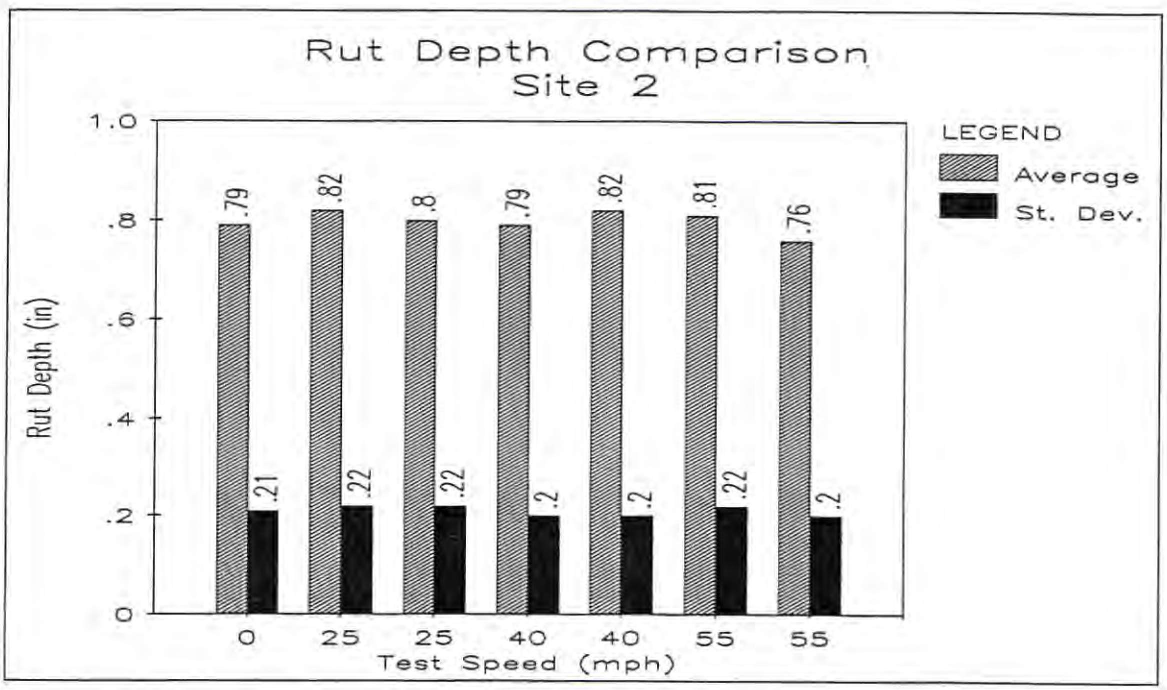


Figure 53: Site 2 Rut Depth Averages

RUT012: Rut Depth Plot Program

Demonstration Project 72; Site # 2
Highway: 1034 From 214.00 + 0.00 to 214.00 + 0.19

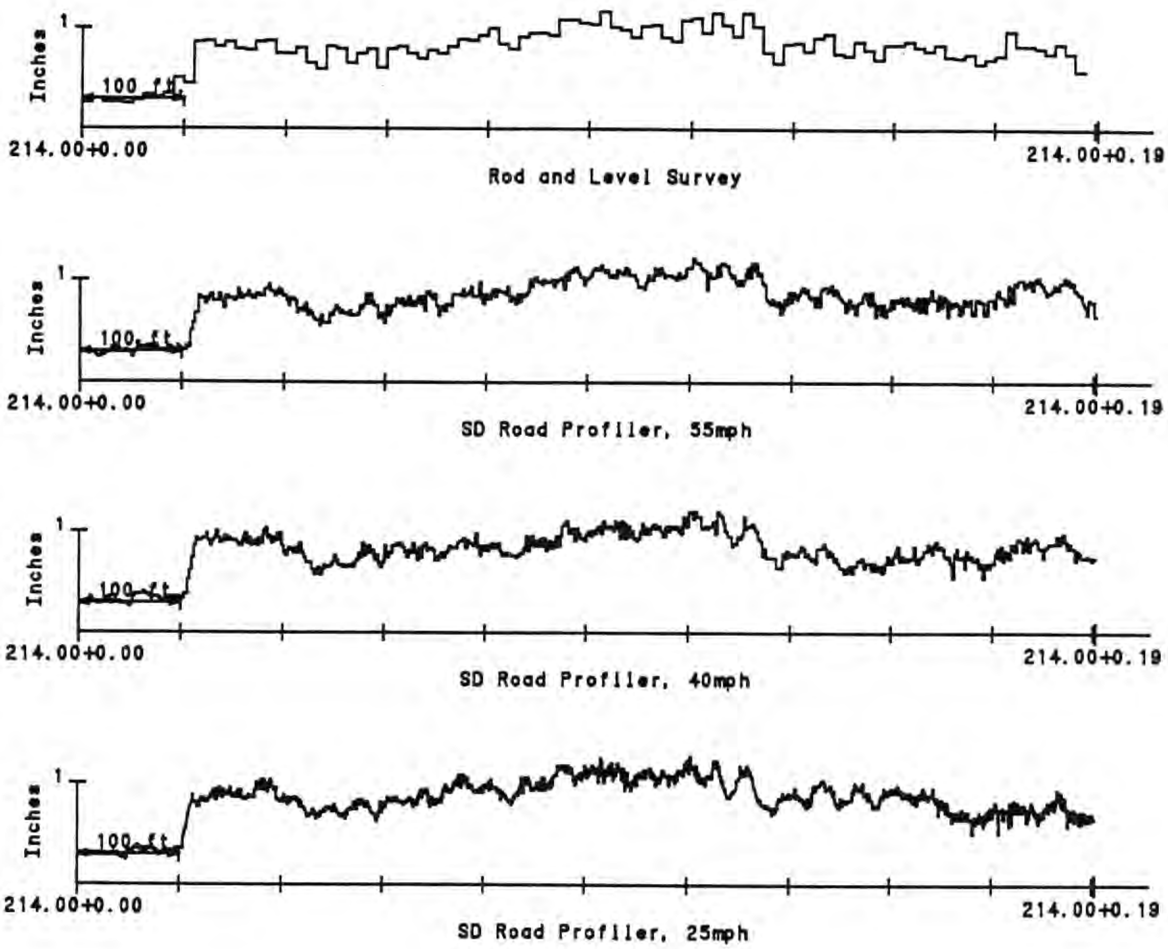


Figure 54: Site 2 Rut Depth Plots

8.3 Site 3

Site 3 is on US14, approximately eight miles west of Pierre (Figure 55). It was part of the same construction project as Site 1, and displayed similar characteristics. Rut depth was not as severe as at Site 1 because Site 3 is on a downhill grade. The pavement's texture was moderate (Figure 56).

Profiles measured by the Road Profiler agree with the manually surveyed profile at both long and short wavelengths (Figures 57 and 58). Their power spectral density plots (Figure 59) show slightly higher content at wavelengths shorter than five feet than does the manual survey's.

International Roughness Indexes obtained by the Road Profiler are similar to the IRI obtained from the manual survey (Figure 60). The manual survey's IRI is 1.16, compared to 1.08-1.15 for the Road Profiler measurements. Present Serviceability Indexes also compare well, although PSIs of the measured profiles improve slightly at higher vehicle speeds.

The average rut depth indicated by manual survey was 0.16 inches (Figure 61) compared to rut depths between 0.14 and 0.19 inches for the Road Profiler. The standard deviation in rut depth measurements was 0.04 inches for the manual survey and all six Road Profiler surveys. The rut depth plots (Figure 62) show good agreement throughout the test section's length.

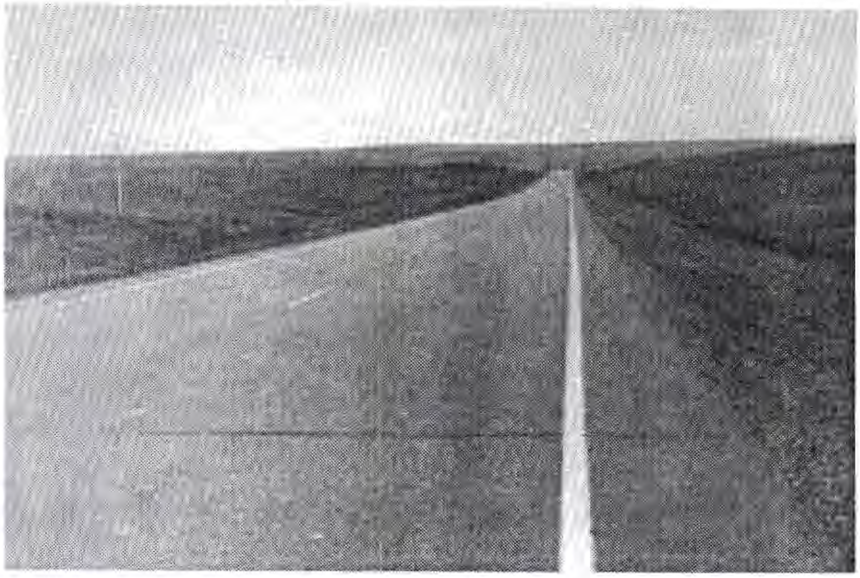


Figure 55: Site 3

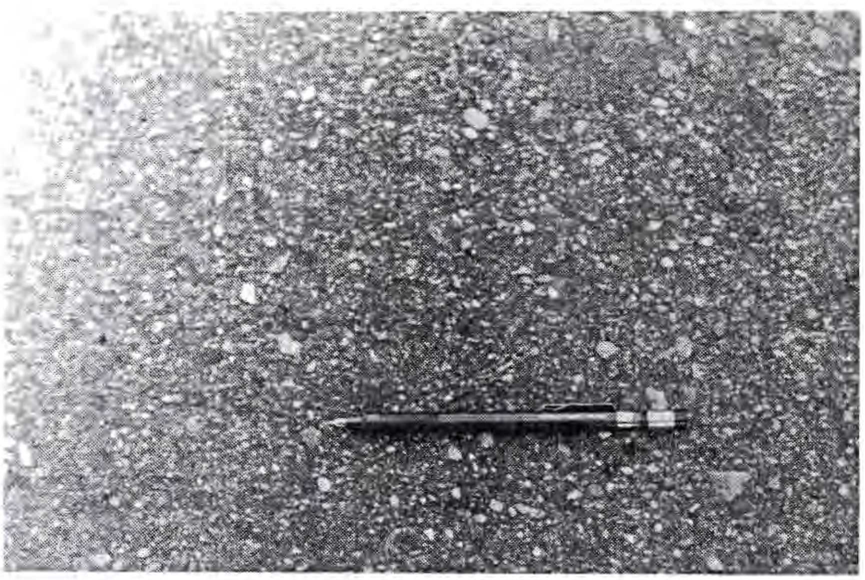


Figure 56: Site 3 Pavement Texture

SITE DATA
Site 3

PRF012: Filtered Profile Plot Program
Copyright 1987 SDDOT

Demonstration Project 72; Site # 3
Highway: 1014 From 219.00 -0.19 to 219.00 + 0.00
Cutoff Wavelength = 1000ft

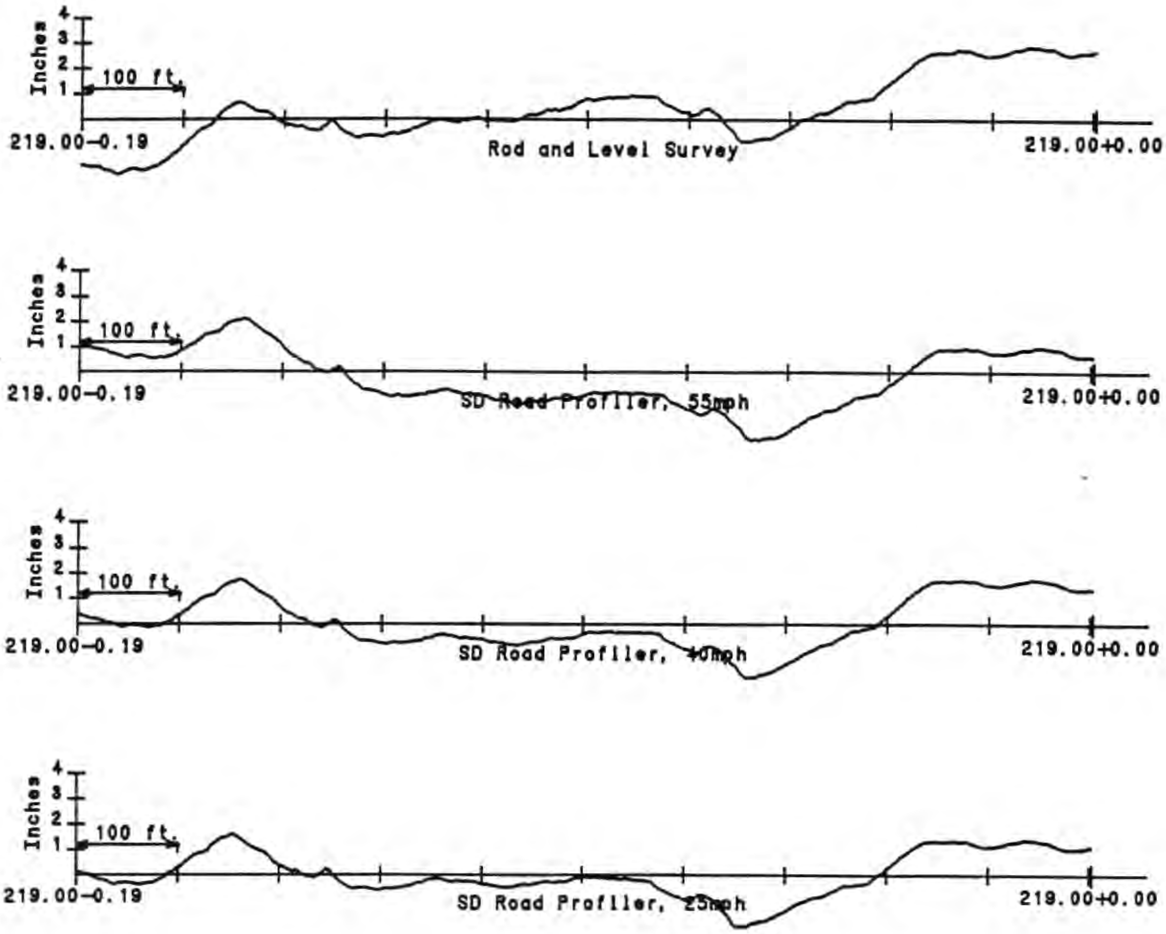


Figure 57: Site 3 Profiles, 1000' Cutoff

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 3
Highway: 1014 From 219.00 -0.19 to 219.00 + 0.00
Cutoff Wavelength = 200ft

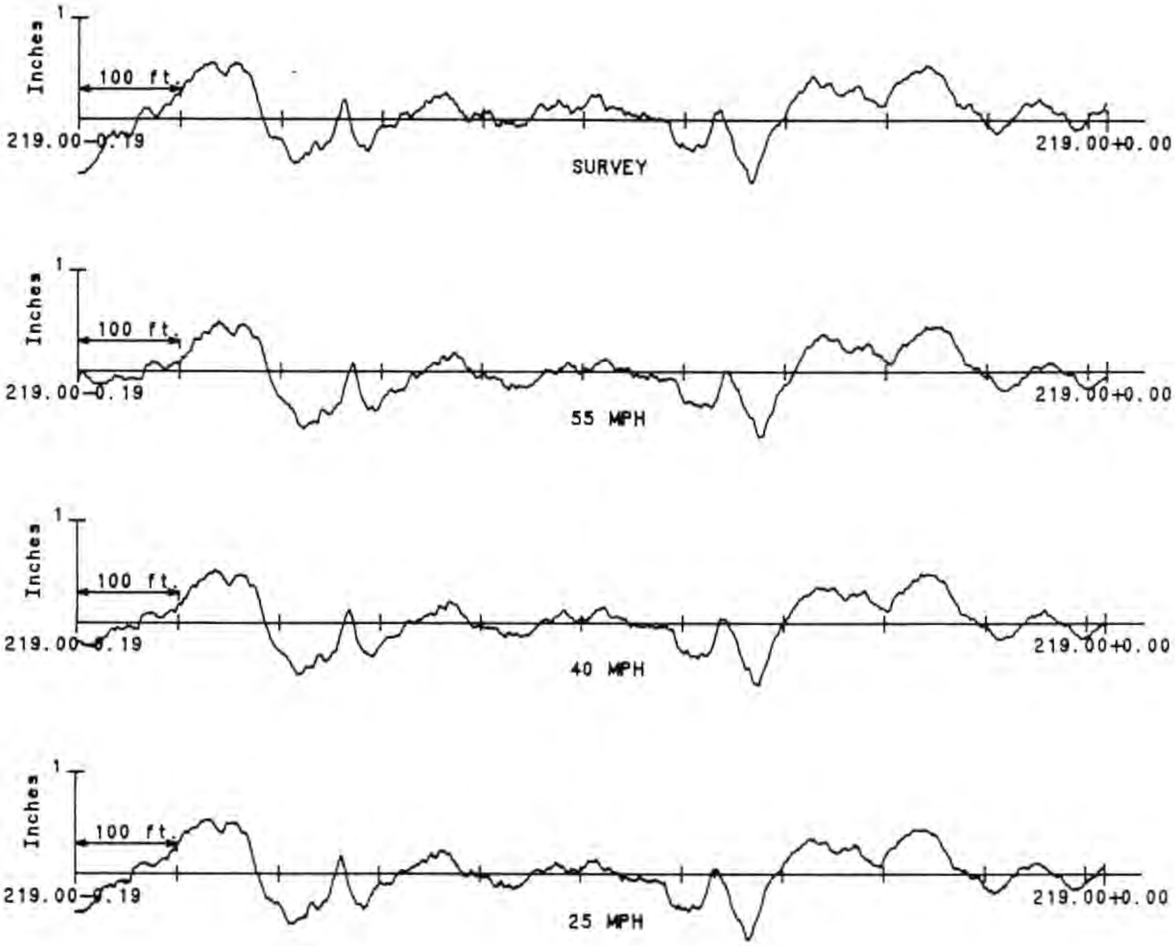


Figure 58: Site 3 Profiles, 200' Cutoff

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site #3
Highway: 1014 From 219.00 –0.19 to 219.00 + 0.00

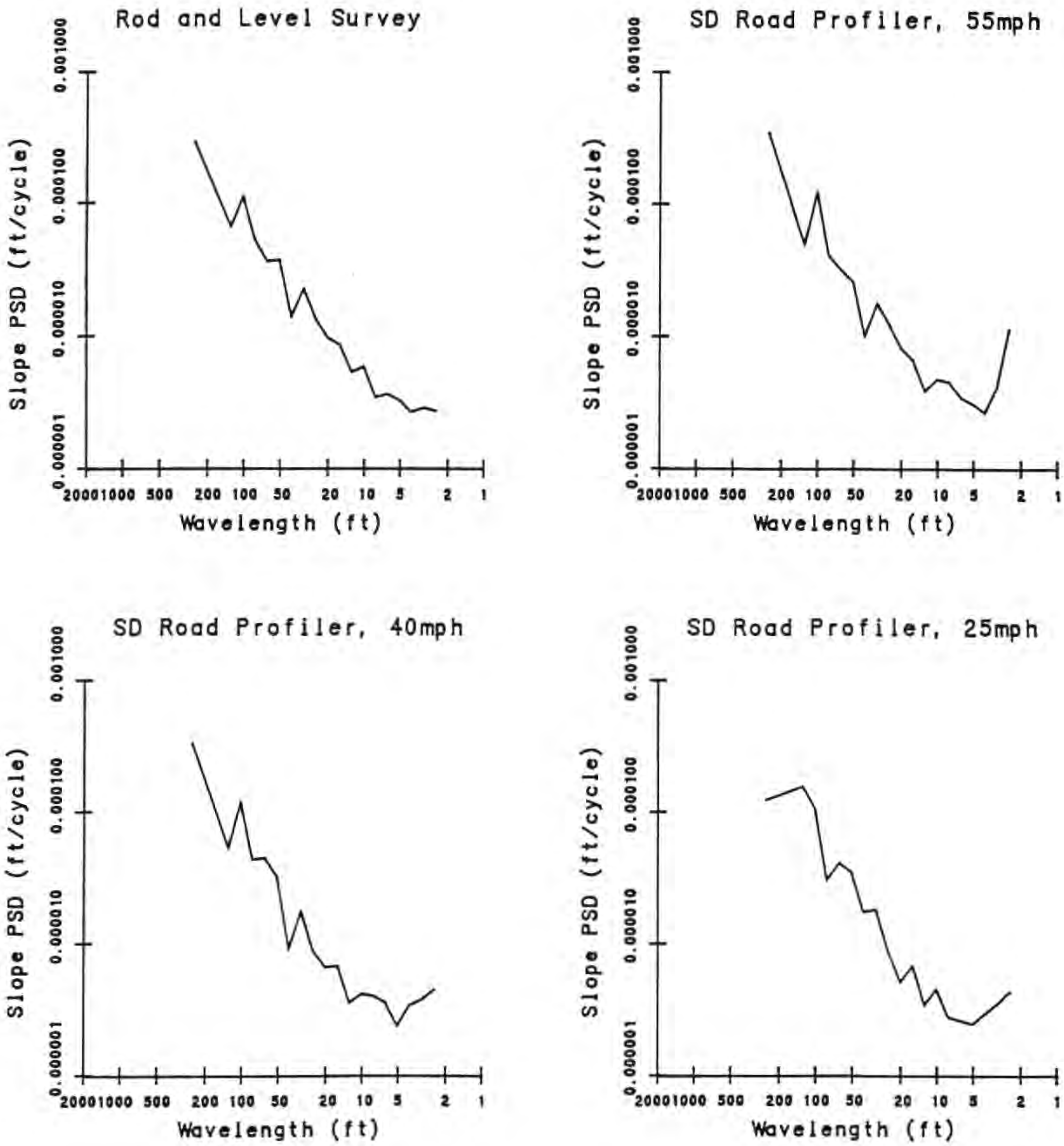


Figure 59: Site 3 Spectral Analysis Plots

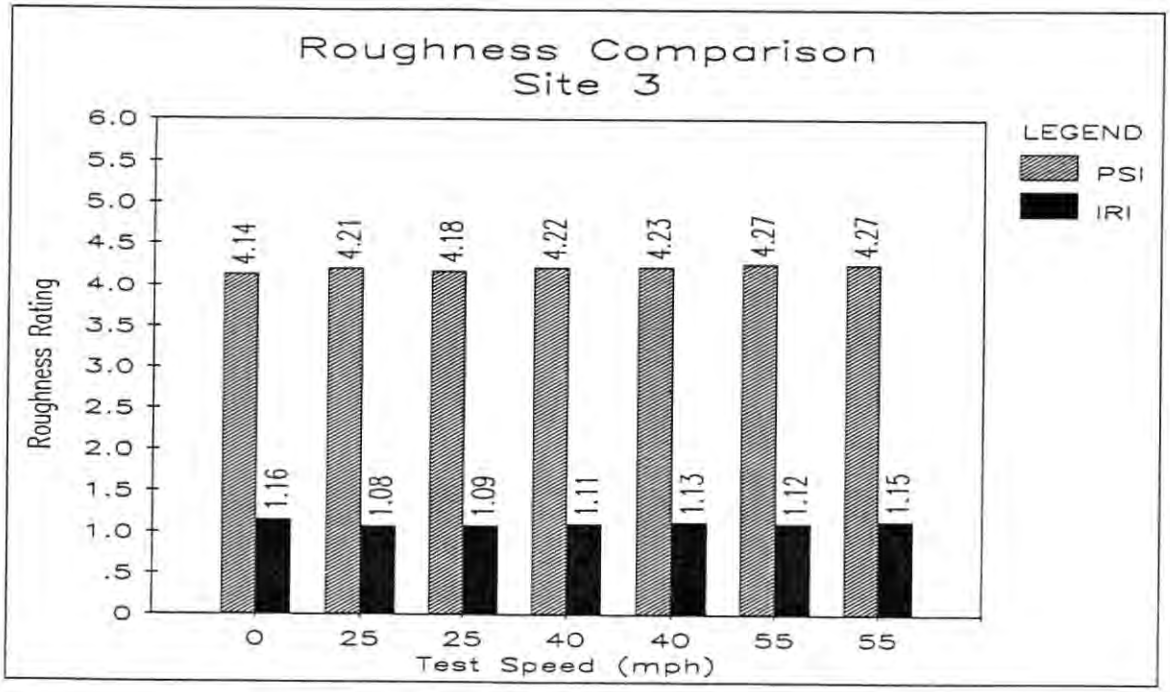


Figure 60: Site 3 Roughness Ratings

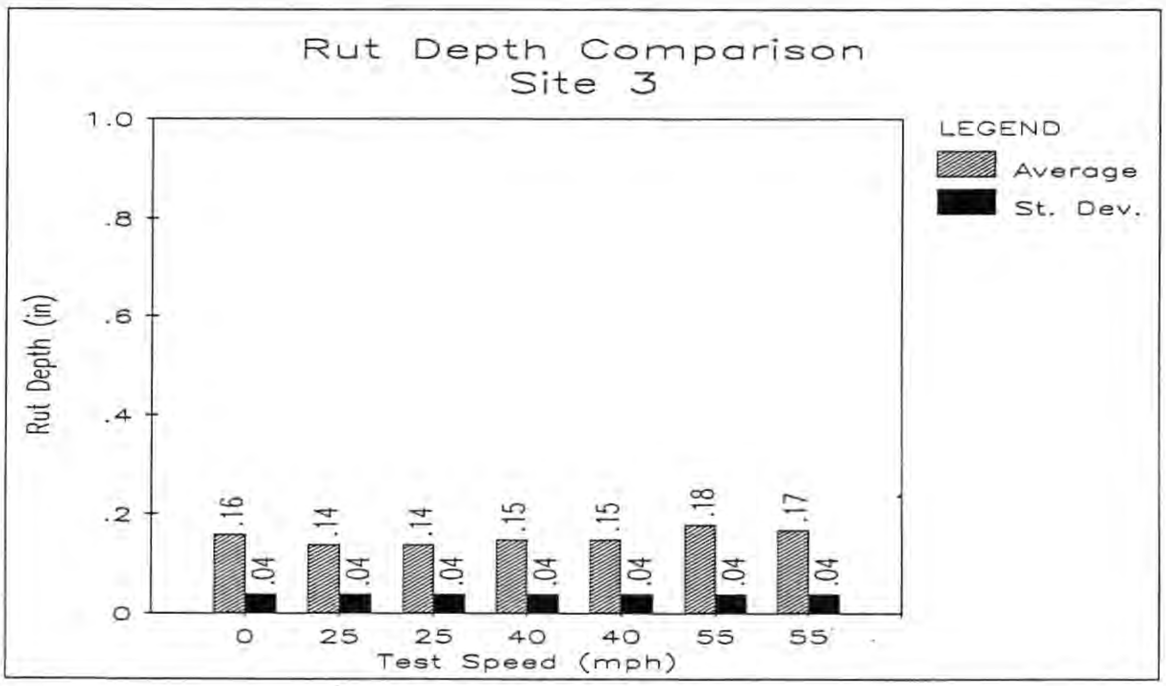


Figure 61: Site 3 Rut Depth Averages

SITE DATA
Site 3

RUT012: Rut Depth Plot Program
Copyright 1987 SDDOT

Demonstration Project 72; Site # 3
Highway: 1014 From 219.00 -0.19 to 219.00 + 0.00

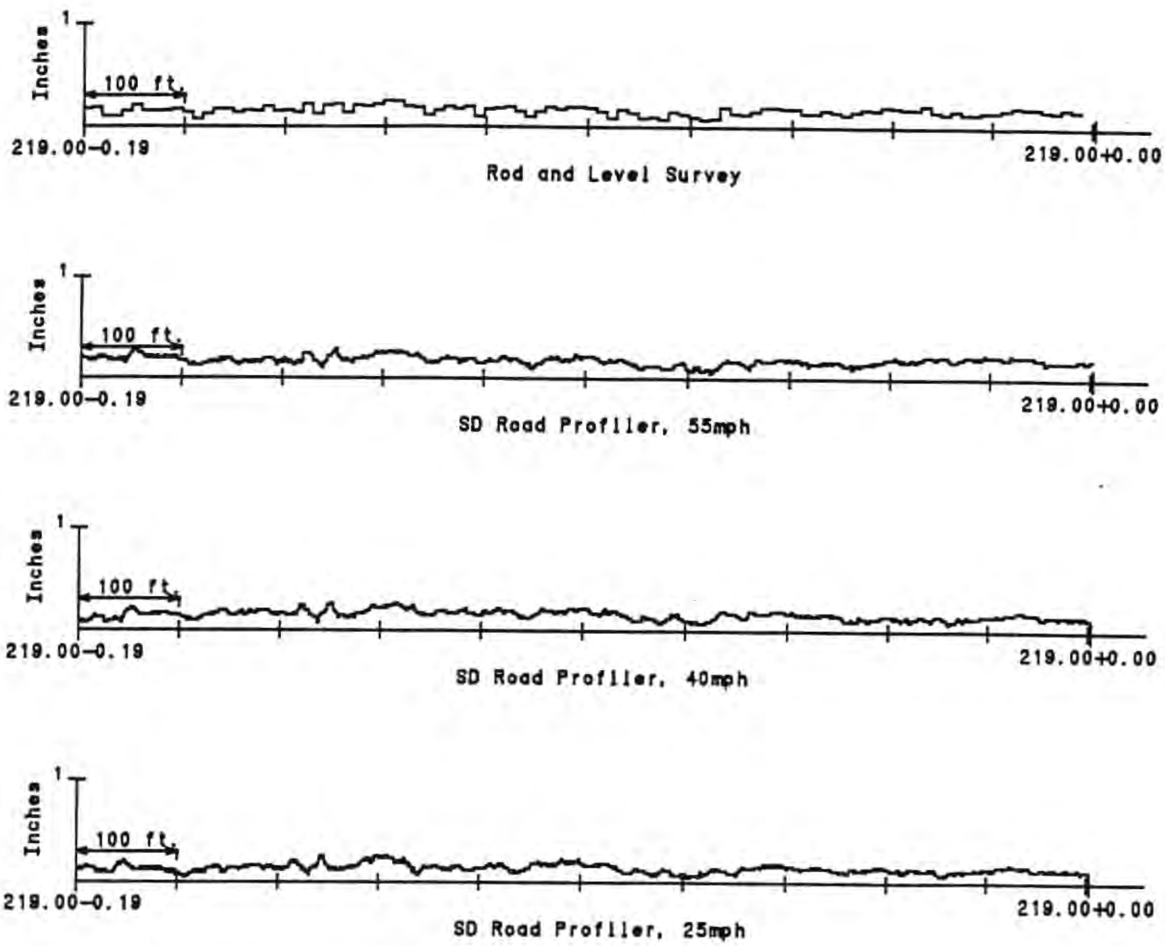


Figure 62: Site 3 Rut Depth Plots

8.4 Site 4

Site 4 is on SD1806, approximately three miles west of Pierre (Figure 63). It was constructed in 1963 with 3" of bituminous mat atop 11" of untreated base. In 1985, a 2" asphalt overlay and a coarse chip seal were placed. When tested, rut depths approached 0.5". The surface texture was moderately coarse, with aggregate protruding approximately 0.05" (Figure 64).

Profiles measured by the Road Profiler show good agreement with the manual survey at long and short wavelengths (Figures 65 and 66). Power spectral density plots (Figure 67) also agree well, with some variation around the fifty foot wavelength.

International Roughness Indexes for the measured profiles are within 0.08 mm/m of the manually surveyed profile's IRI of 1.62 mm/m (Figure 68). Present Serviceability Indexes are somewhat higher for the measured profiles than for the manually surveyed profile.

The average rut depths measured by the Road Profiler are all within 0.02 inches of the manually surveyed average rut depth (Figure 69). Standard deviations are also nearly identical. Although rut depth is variable throughout the test section, there is good agreement between the manual and Road Profiler surveys (Figure 70).

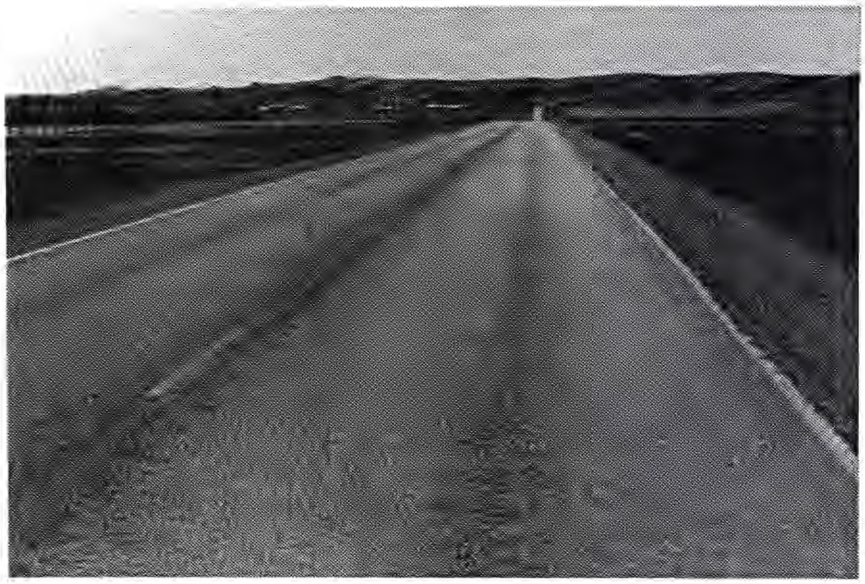


Figure 63: Site 4

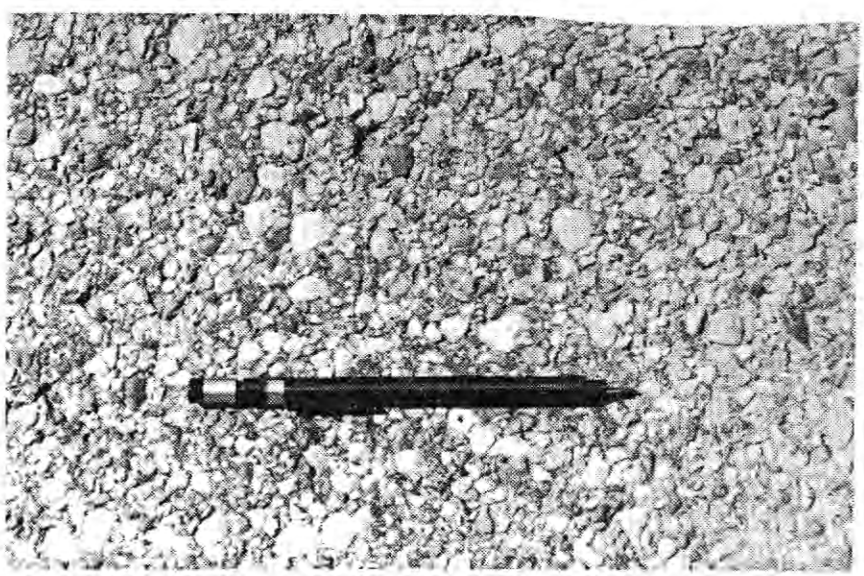


Figure 64: Site 4 Pavement Texture

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 4
Highway: 11806   From 188.00 -0.19 to 188.00 + 0.00
Cutoff Wavelength = 1000ft

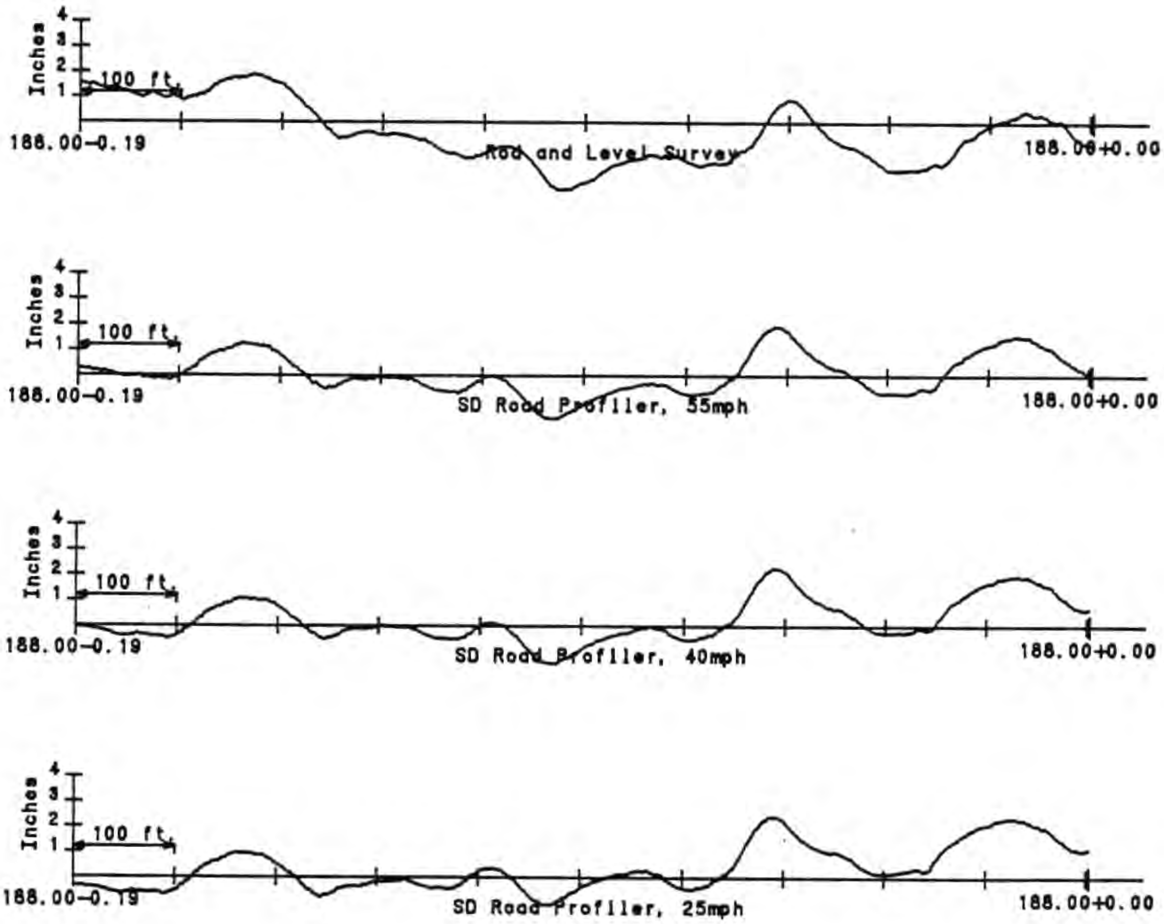


Figure 65: Site 4 Profiles, 1000' Cutoff

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 4
Highway: 11806   From 188.00 -0.19 to 188.00 + 0.00
Cutoff Wavelength = 200ft

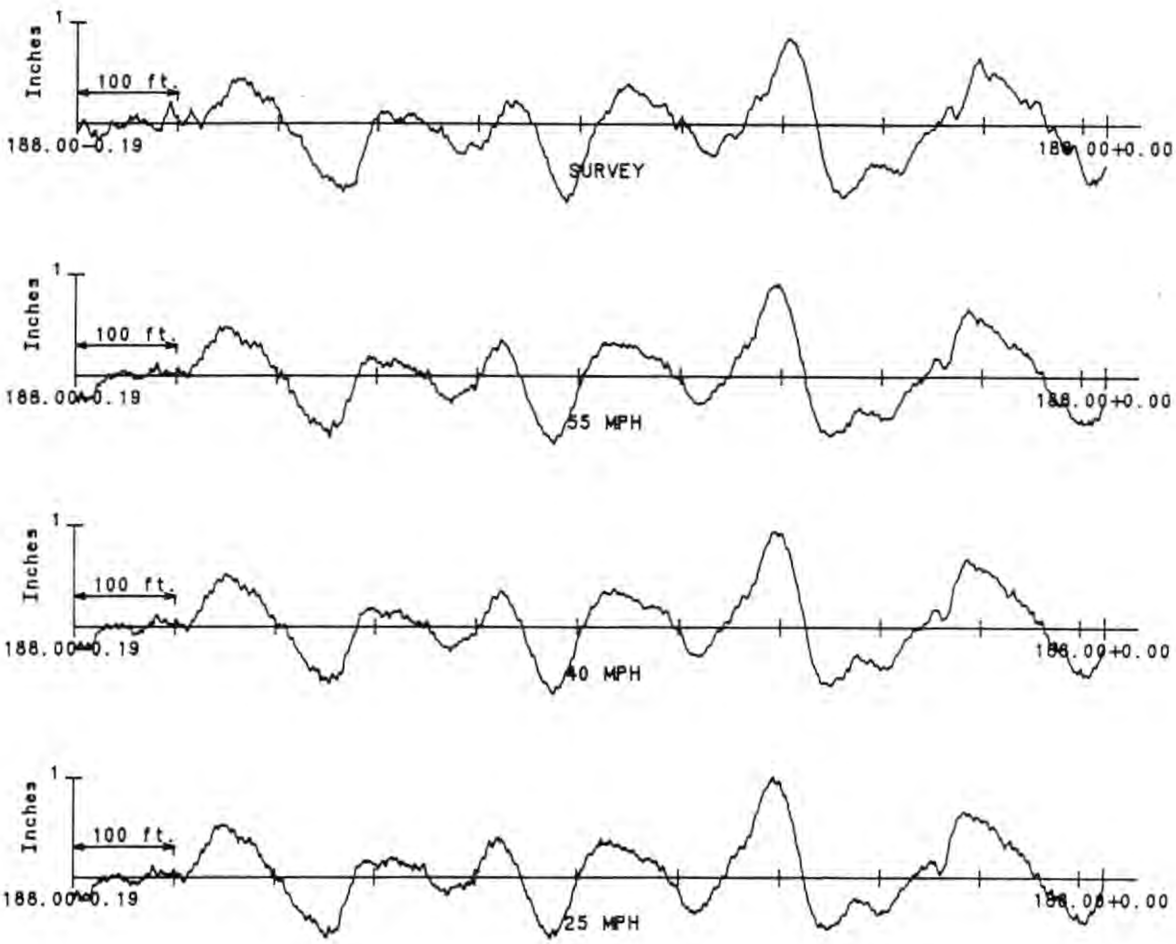


Figure 66: Site 4 Profiles, 200' Cutoff

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site # 4
Highway: 11806 From 188.00 -0.19 to 188.00 + 0.00

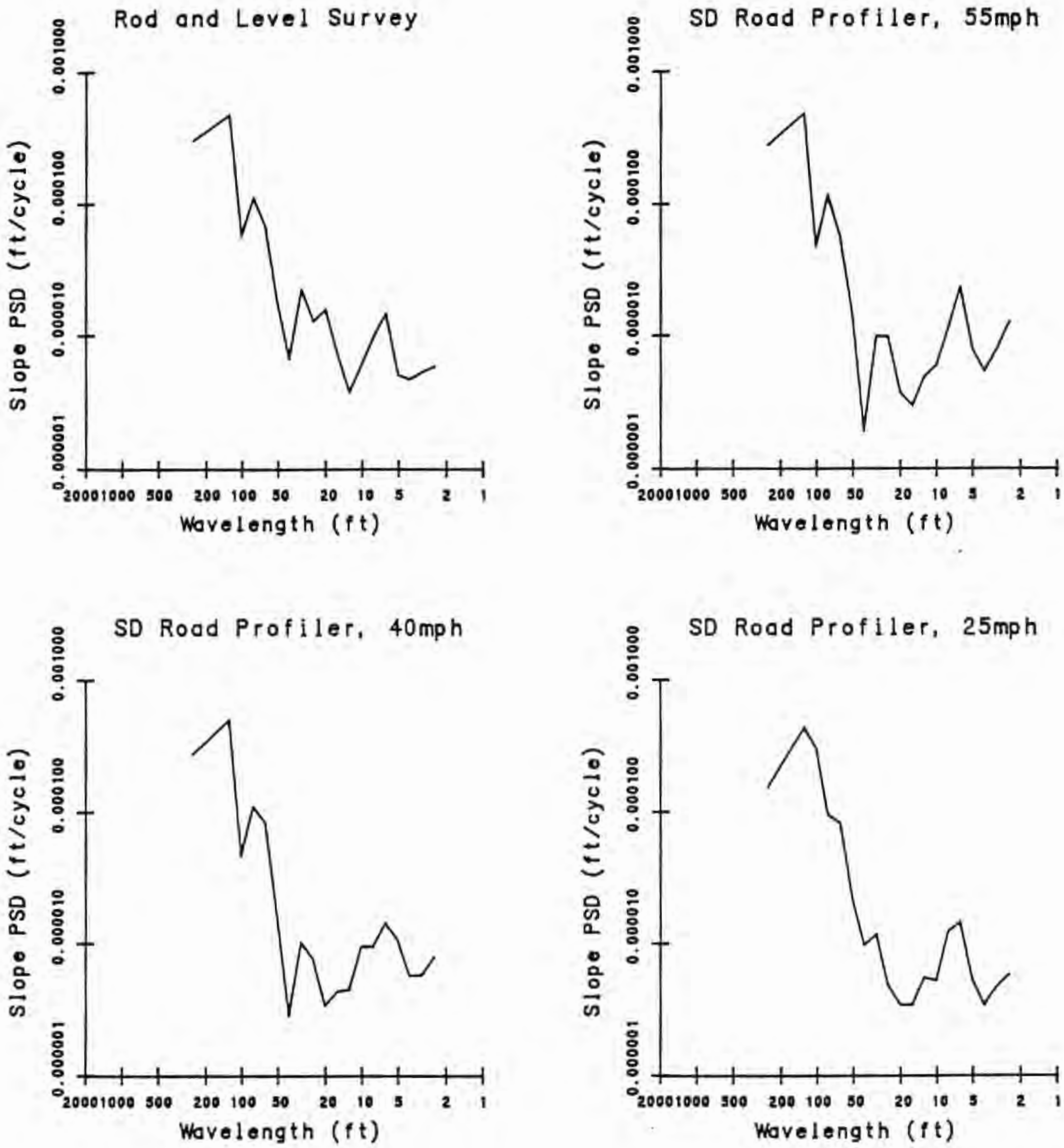


Figure 67: Site 4 Spectral Analysis Plots

SITE DATA
Site 4

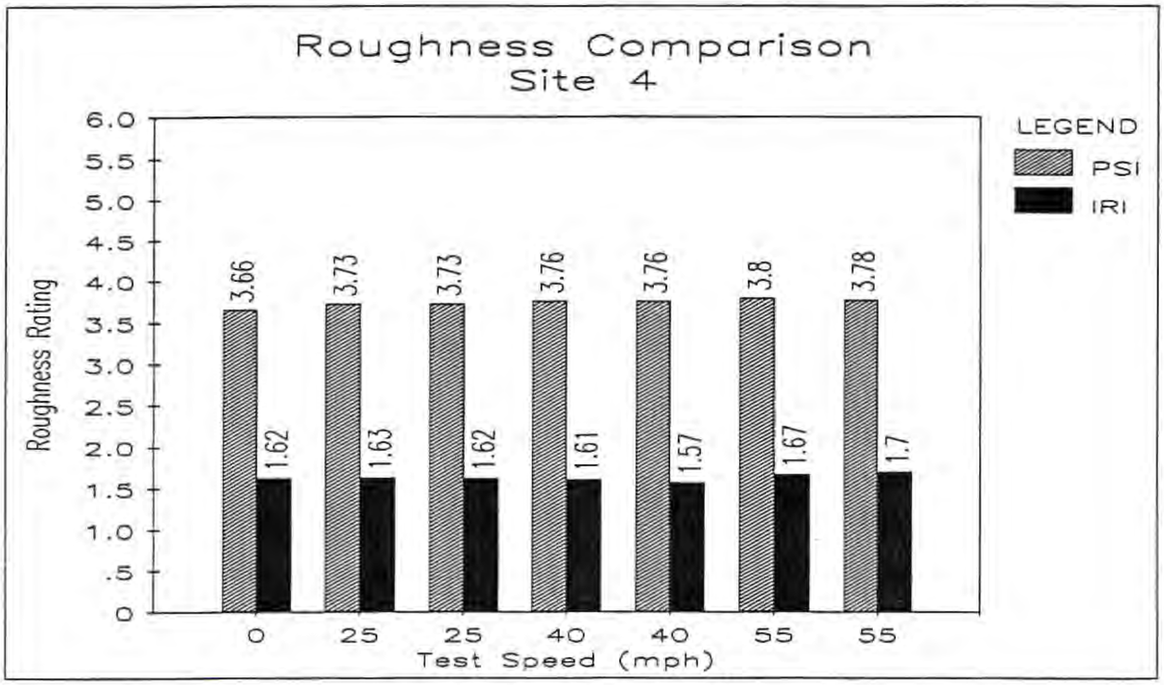


Figure 68: Site 4 Roughness Ratings

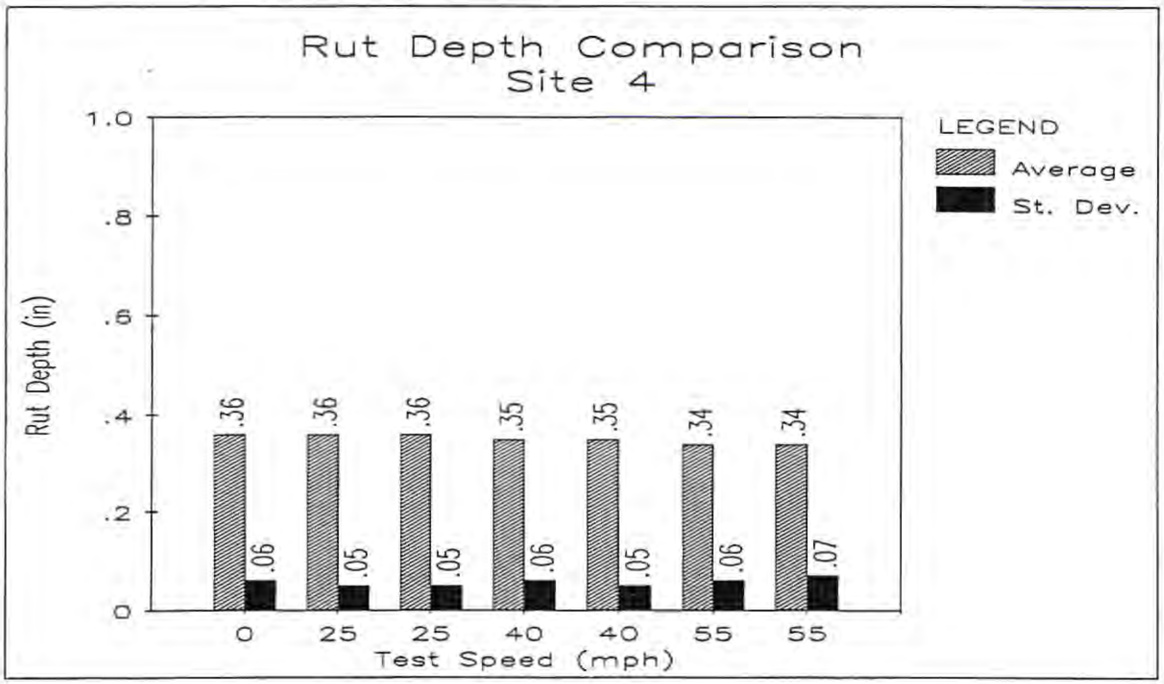
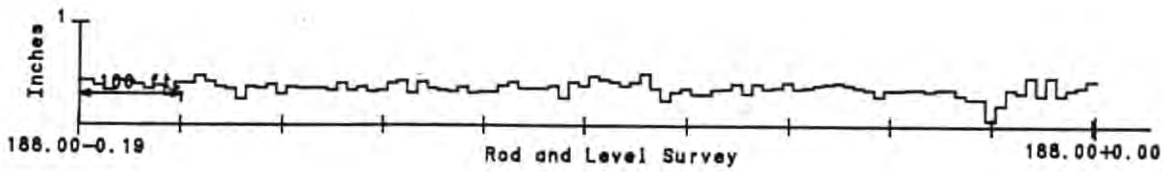
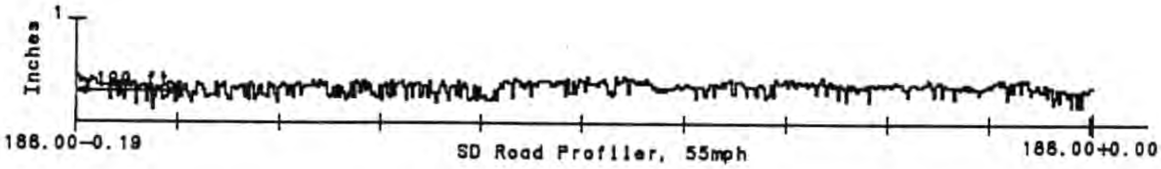


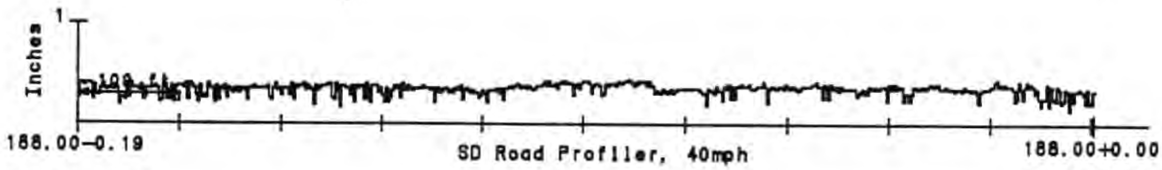
Figure 69: Site 4 Rut Depth Averages

RUT012: Rut Depth Plot Program

Demonstration Project 72; Site # 4
Highway: 11806 From 188.00 -0.19 to 188.00 + 0.00







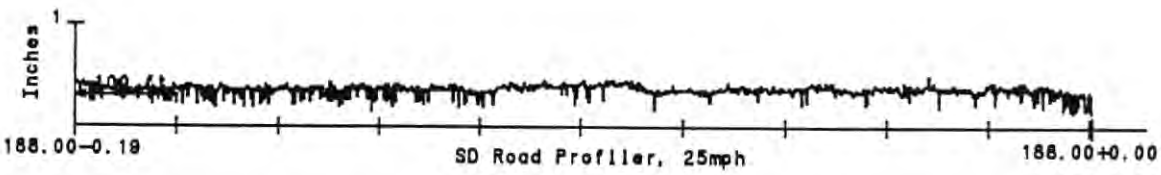


Figure 70: Site 4 Rut Depth Plots

8.5 Site 5

Site 5 is on SD1806, approximately eighteen miles northwest of Pierre (Figure 71). It was constructed in 1970, and topped with a surface treatment on 6" of untreated base in 1972. In 1979, the road was resurfaced with 5" of lime treated base and 1.5" of asphalt pavement. Site 5 is in a remote location, and experiences mostly farm-to-market traffic. When tested, the surface was quite irregular because of expansive soils and truck traffic. Rut depths exceeded 0.75" in places, and the pavement was cracked transversely. In places, the pavement had shoved out towards the shoulder. A chip seal which was placed in 1985 presented a very coarse texture (Figure 72).

Profiles measured by the Road Profiler show good agreement with the manual survey at long wavelengths (Figure 73), but contain more short wavelength variations (Figure 74). Power spectral density plots (Figure 75) show the measured profiles' significantly higher content at wavelengths shorter than five feet.

The measured profiles' International Roughness Indexes are higher than the manually surveyed profile's IRI (Figure 76). The Road Profiler's IRIs range from 2.75 to 3.05, compared to 2.67 for the manual survey. The measured profiles' Present Serviceability Indexes also vary, but the trend is opposite that of the IRI. Whereas IRI generally worsens with increasing speed, PSI improves.

At Site 5, rut depths measured by the Road Profiler are higher than those measured by manual survey (Figure 77). The pavement's shoving toward the shoulder may have contributed to this difference. Rut depth is also more variable than at other sites (Figure 78), probably because of subgrade and surfacing failures under heavy truck traffic.

Figure 71: Site 5

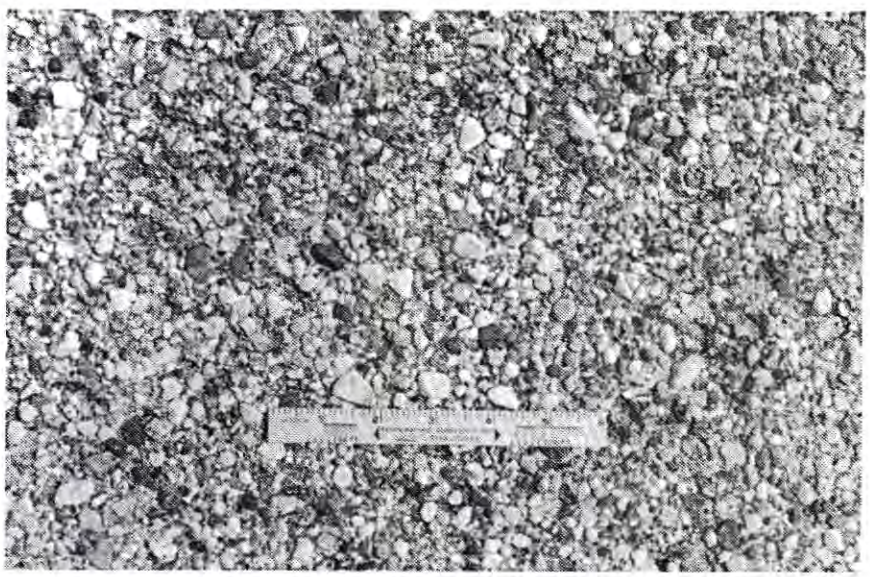


Figure 72: Site 5 Pavement Texture

SITE DATA
Site 5

PRF012: Filtered Profile Plot Program

Copyright 1987 SDDOT

Demonstration Project 72; Site # 5
Highway: 11806 From 203.00 -0.19 to 203.00 + 0.00
Cutoff Wavelength = 1000ft

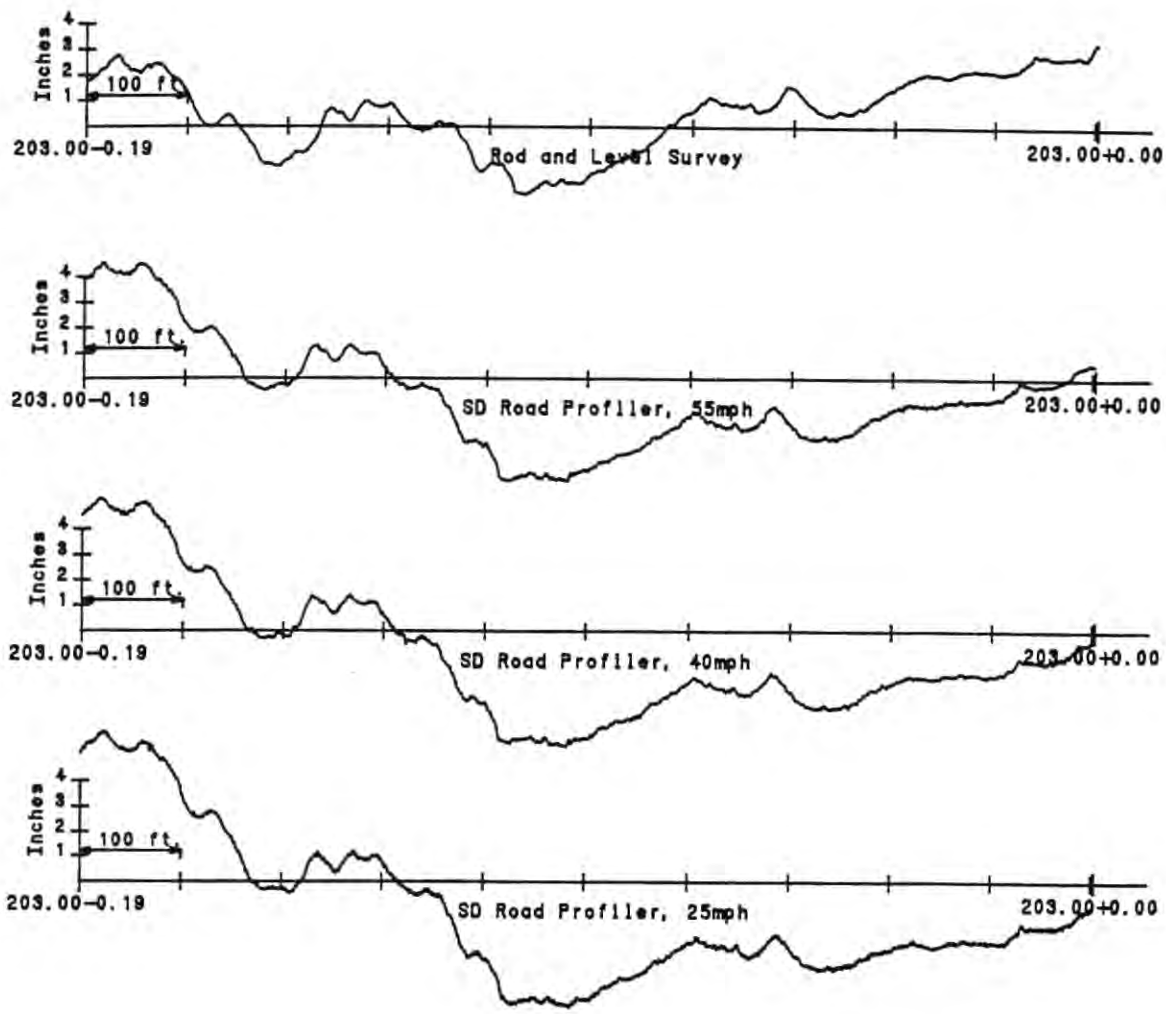


Figure 73: Site 5 Profiles, 1000′ Cutoff

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 5
Highway: 11806 From 203.00 -0.19 to 203.00 + 0.00
Cutoff Wavelength = 200ft

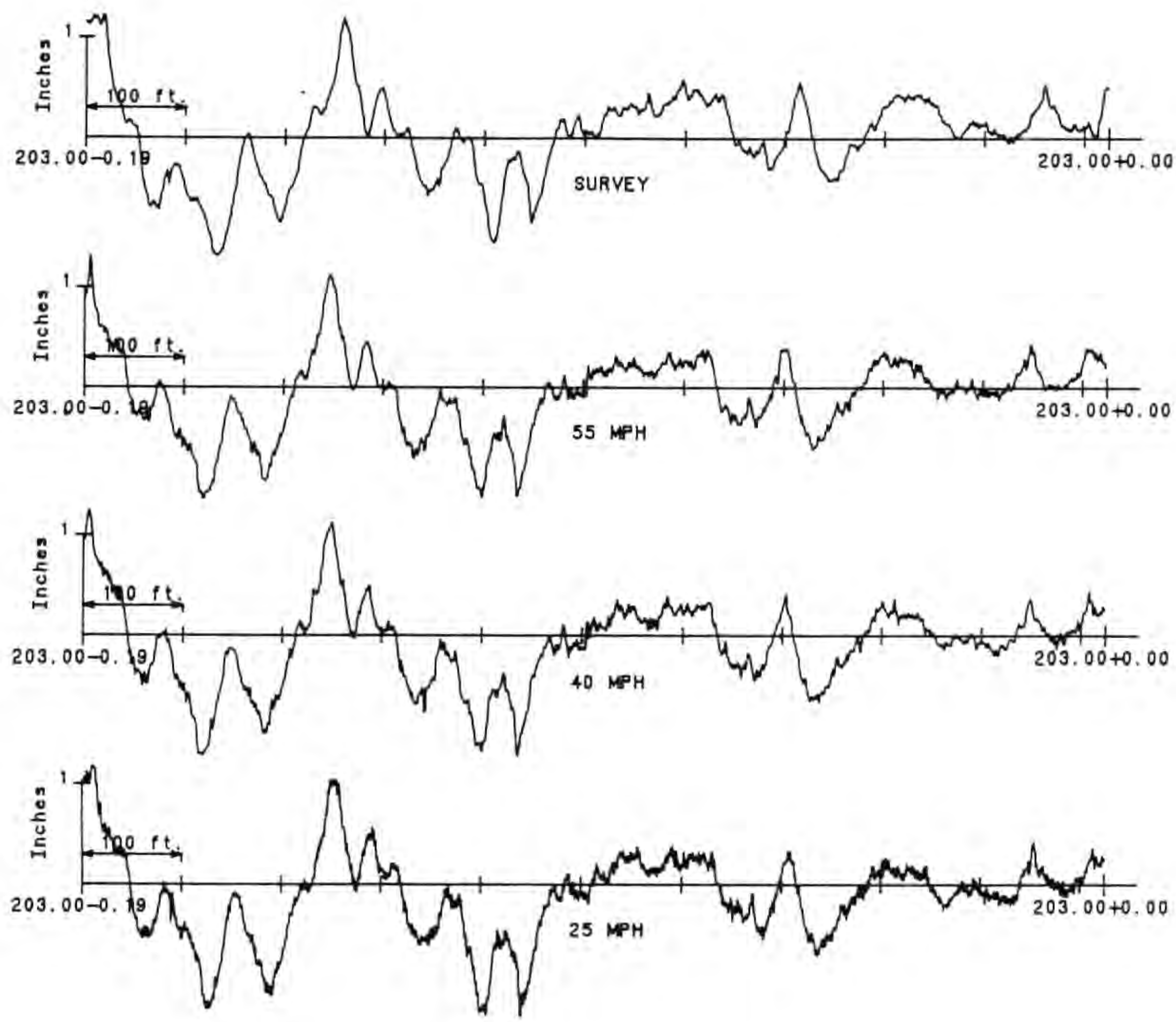


Figure 74: Site 5 Profiles, 200' Cutoff

SITE DATA
Site 5

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site # 5
Highway: 11806   From 203.00 -0.19 to 203.00 + 0.00

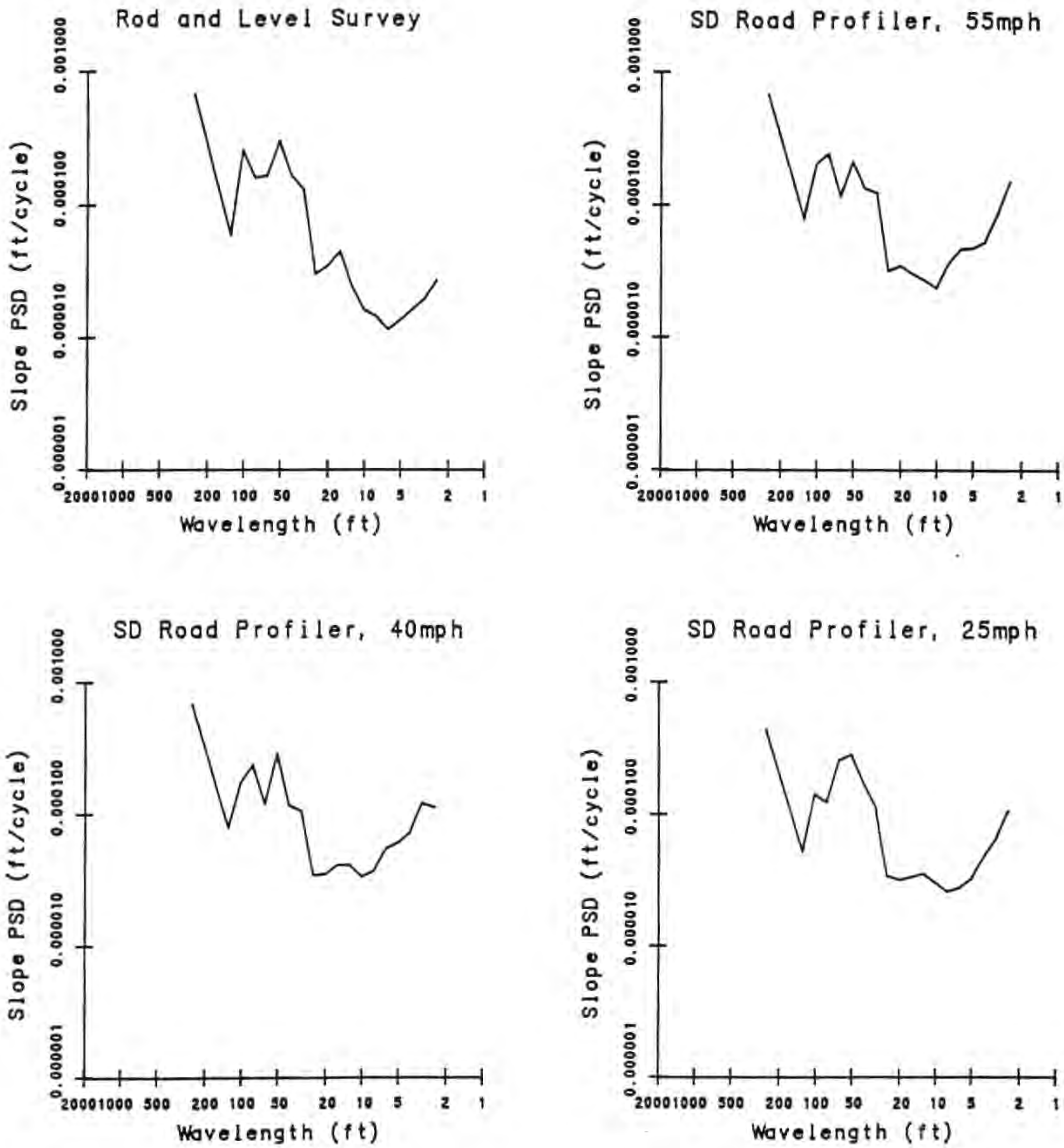


Figure 75: Site 5 Spectral Analysis Plots

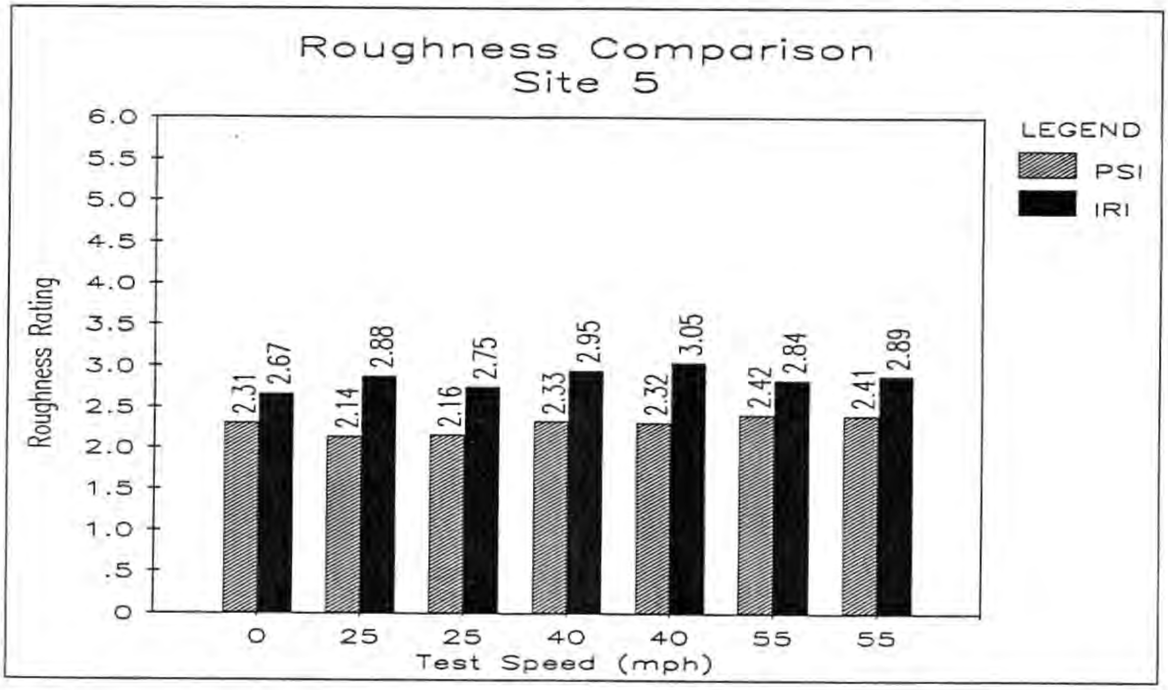


Figure 76: Site 5 Roughness Ratings

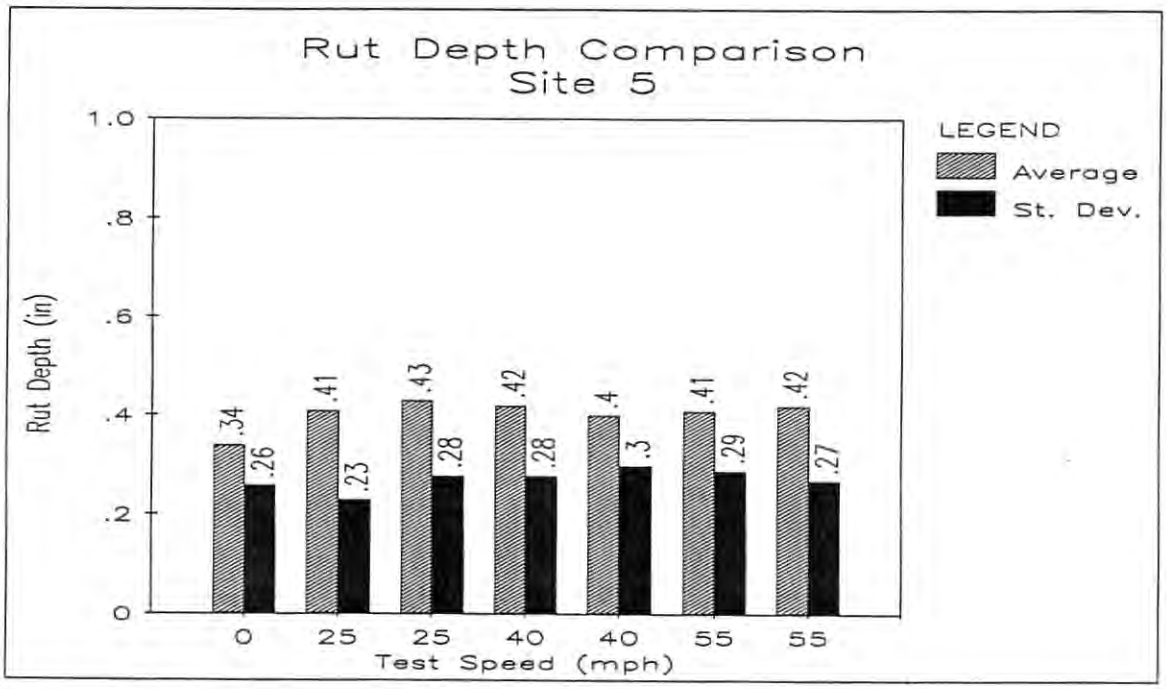


Figure 77: Site 5 Rut Depth Averages

RUT012: Rut Depth Plot Program

Demonstration Project 72; Site # 5
Highway: 11806 From 203.00 -0.19 to 203.00 + 0.00

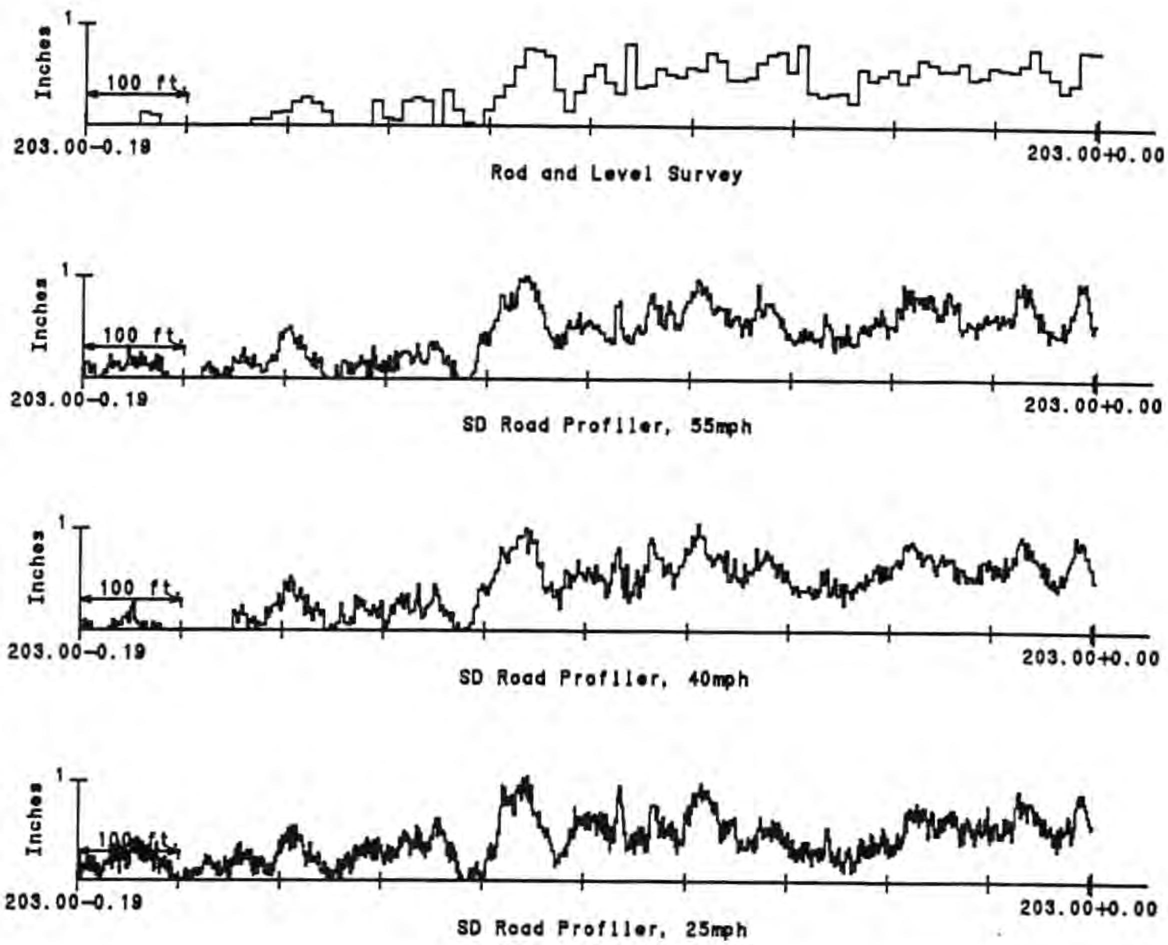


Figure 78: Site 5 Rut Depth Plots

8.6 Site 6

Site 6 is on US83 approximately two miles south of Pierre (Figure 79). It was constructed in 1957 of 2.5 inches of asphalt pavement atop an untreated base six to nine inches thick. In 1980, a 1.5 inch asphalt overlay was added and in 1984, a chip seal was applied. When tested, rutting up to 0.5" was evident. Transverse cracks approximately three-quarters of an inch wide were spaced at intervals of about 80 feet. Surface texture was moderately coarse, with aggregate exposed to a height of about one-sixteenth inch (Figure 80).

Site 6 profiles displayed considerable long wavelength content (Figure 81). A vertical curve longer than 1000 feet is plainly evident in all plots. It is not as strong in the measured profiles as in the manual survey, however, because the Road Profiler attenuates very long wavelengths as it measures profiles. When plotted with a cutoff wavelength of 200 feet, the profiles appear much more similar (Figure 82). Profiles measured by the Road Profiler show more content at wavelengths shorter than five feet than does the manual survey, especially at 55 mph (Figure 83).

International Roughness Indexes computed for the higher speed Road Profiler profiles are somewhat higher than the manual survey's IRI (Figure 84). The indexes appear to correlate with the profiles' short wavelength content. The Present Serviceability Indexes of the Road Profiler profiles also vary, but in a direction opposite to the IRIs. IRIs deteriorate slightly with higher speed, but the PSIs improve slightly.

Average rut depths measured by the Road Profiler are slightly higher than that measured by manual survey (Figure 85). Standard deviations are uniformly within 0.01 inch of each other, however. Rut depth plots show consistent measurements throughout the length of the test section (Figure 86).

SITE DATA
Site 6

Figure 79: Site 6

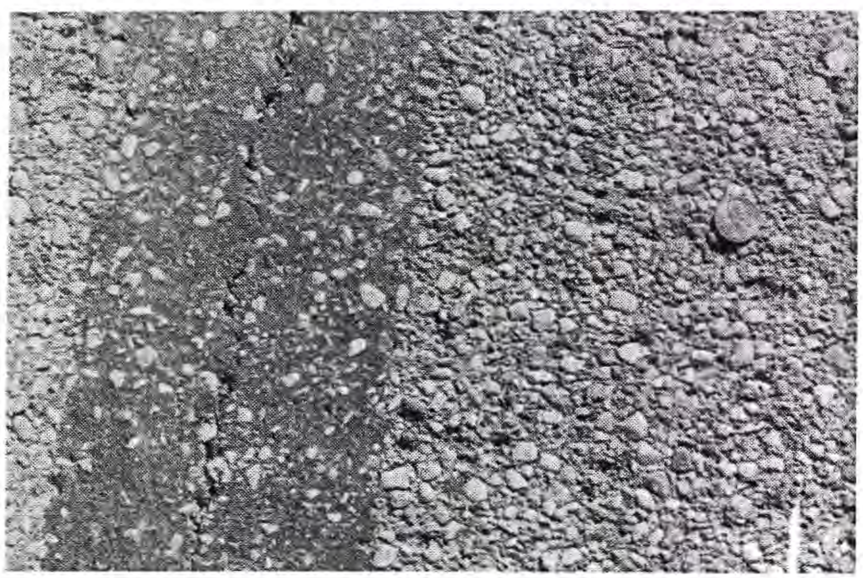


Figure 80: Site 6 Pavement Texture

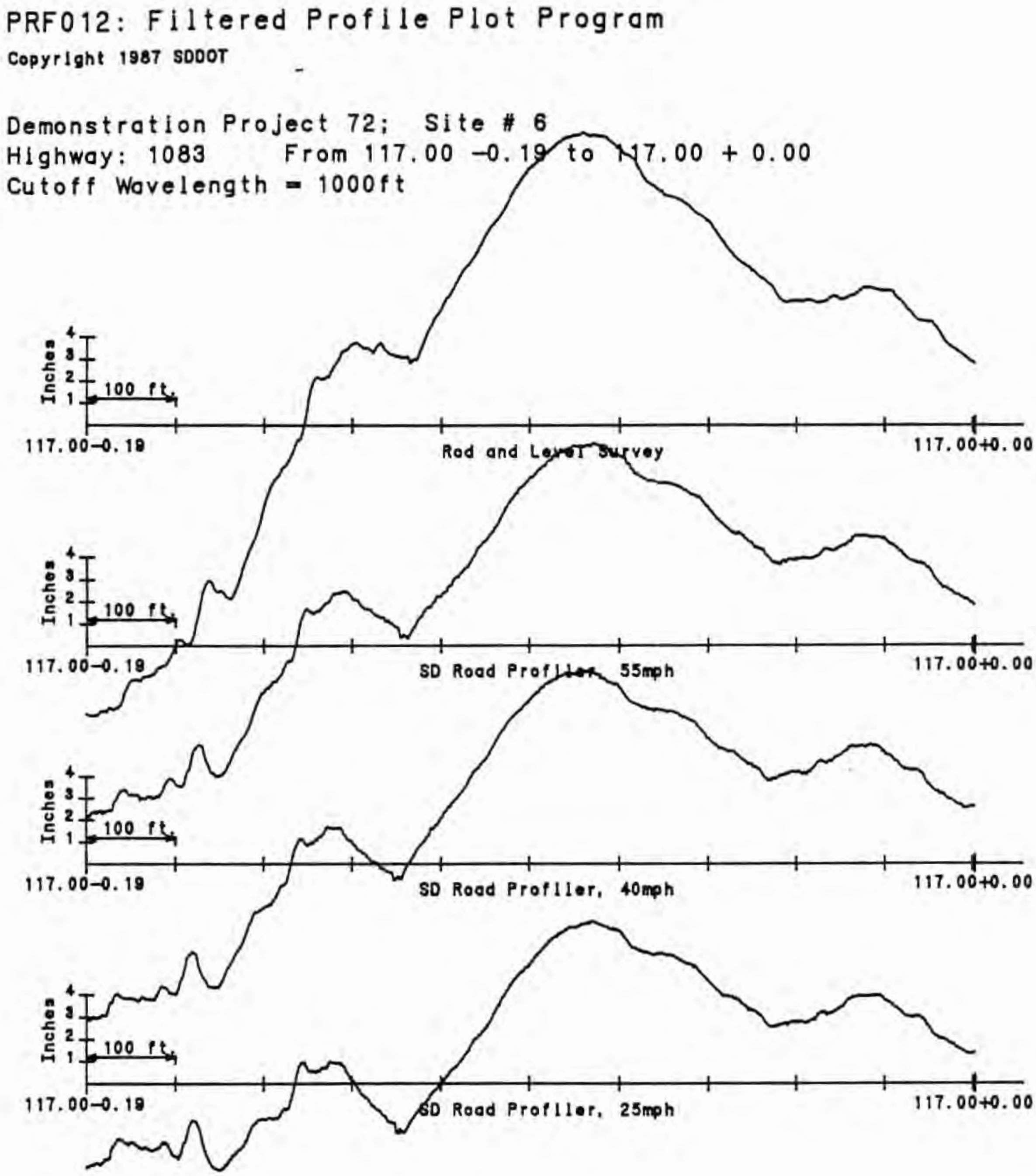


Figure 81: Site 6 Profiles, 1000' Cutoff

SITE DATA
Site 6

PRF012: Filtered Profile Plot Program
Copyright 1987 SDDOT

Demonstration Project 72; Site # 6
Highway: 1083   From 117.00 -0.19 to 117.00 + 0.00
Cutoff Wavelength = 200ft

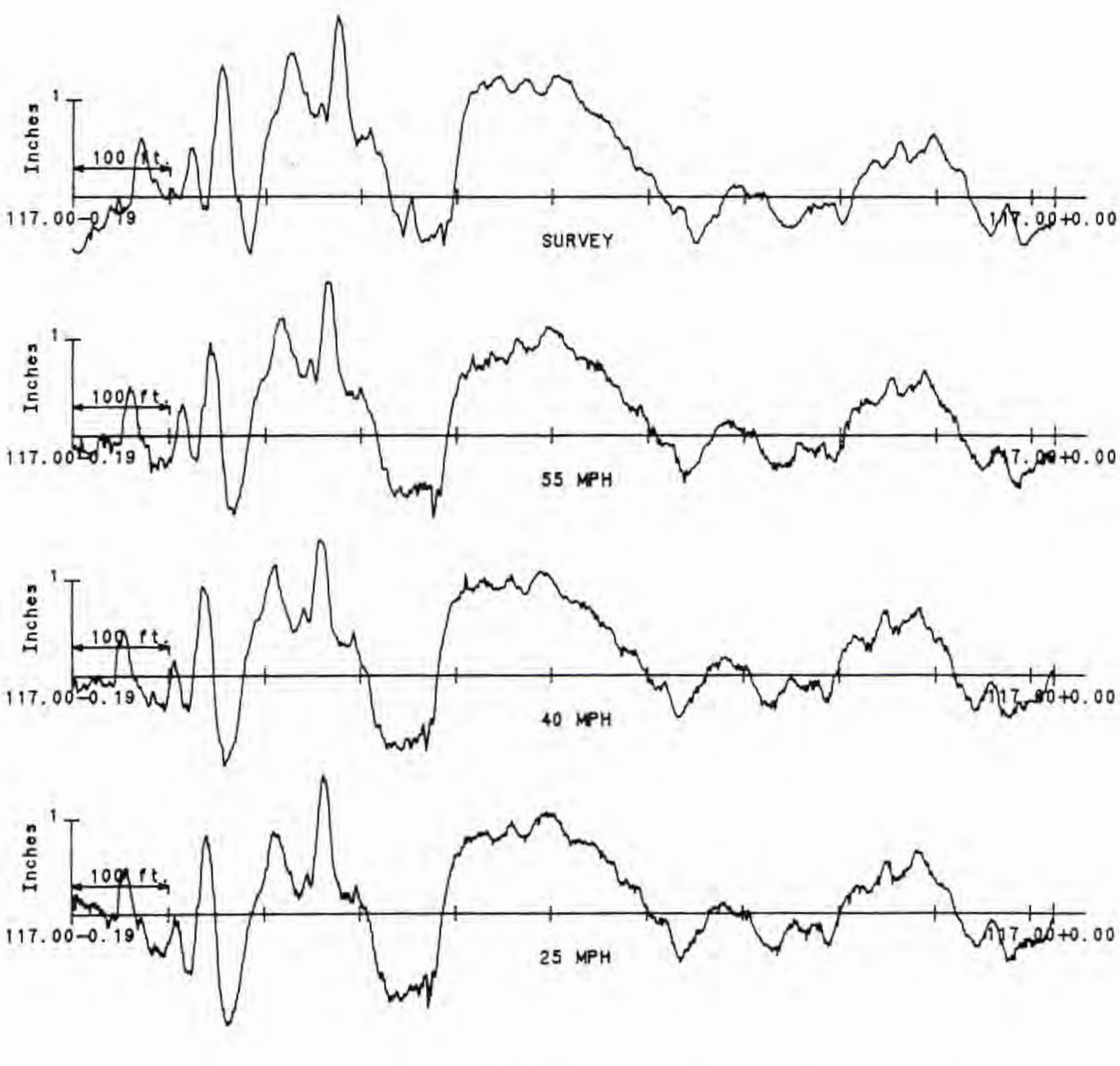


Figure 82: Site 6 Profiles, 200′ Cutoff

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site # 6
Highway: 1083 From 117.00 -0.19 to 117.00 + 0.00

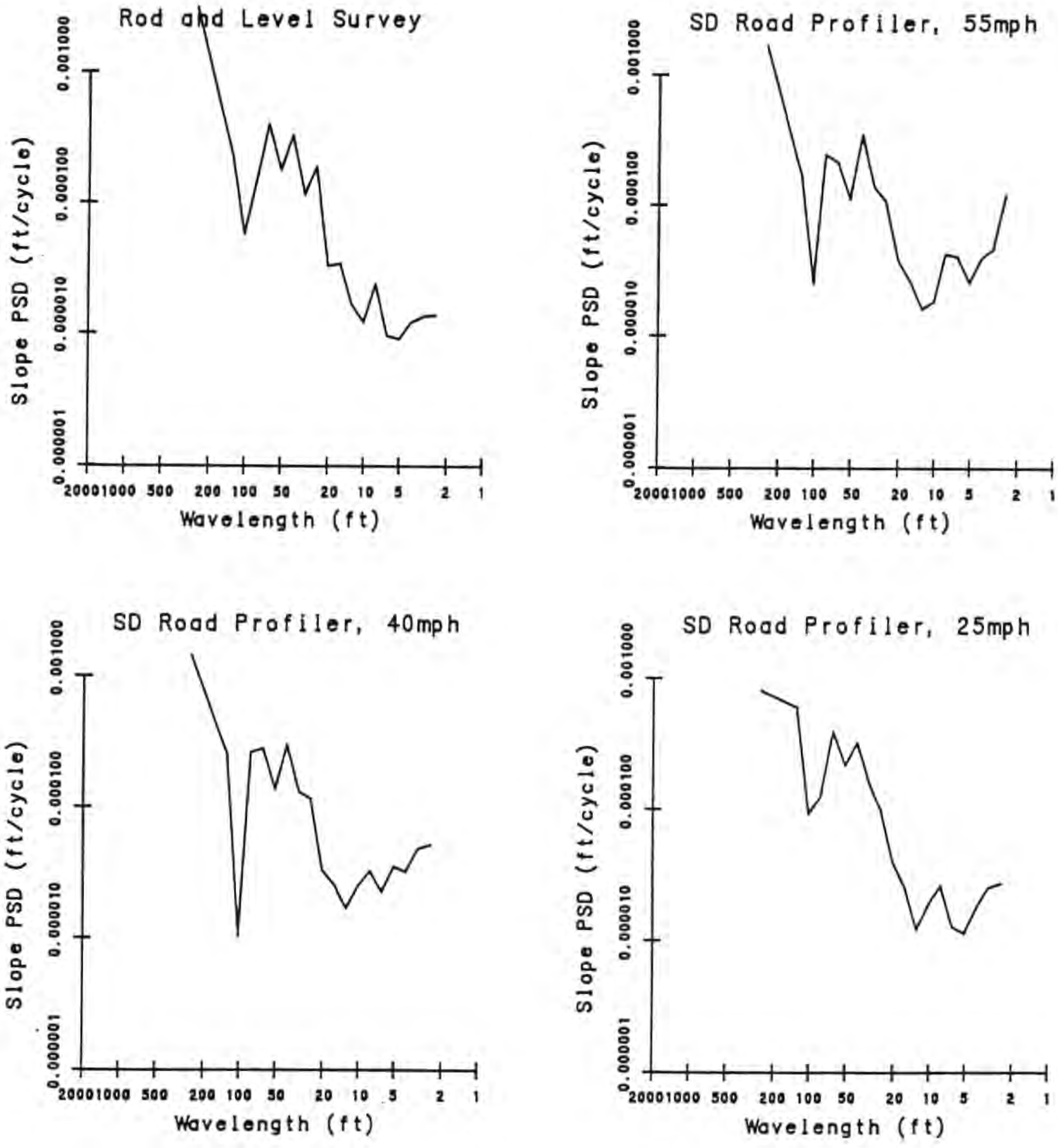


Figure 83: Site 6 Spectral Analysis Plots

SITE DATA
Site 6

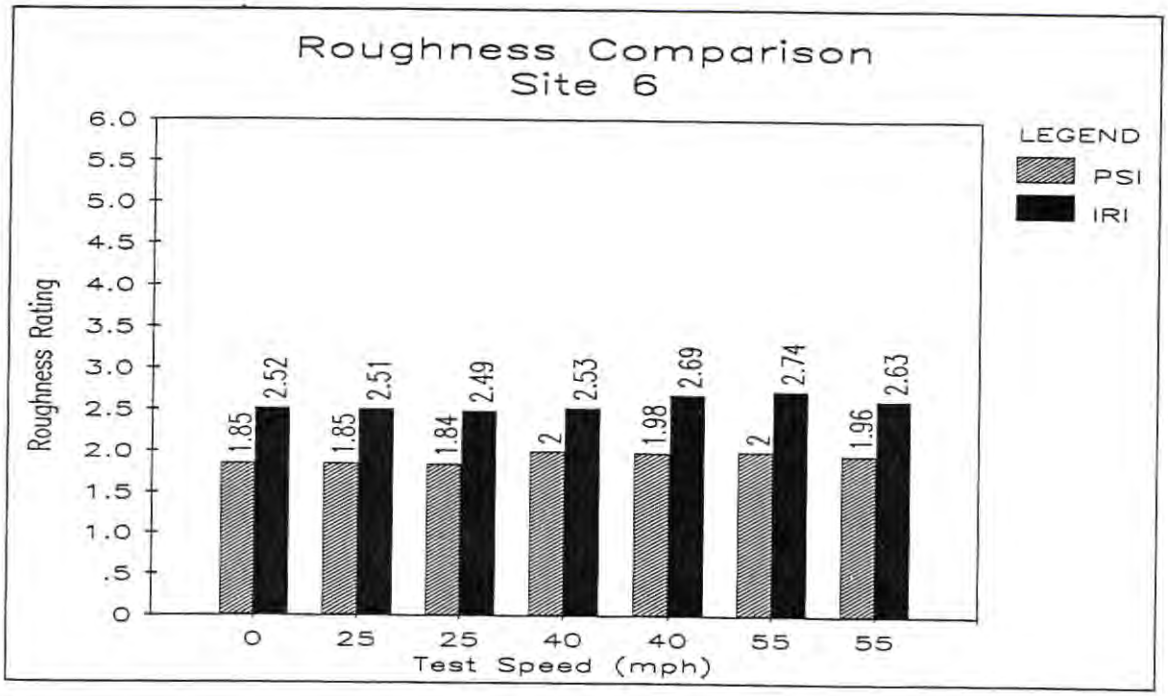


Figure 84: Site 6 Roughness Ratings

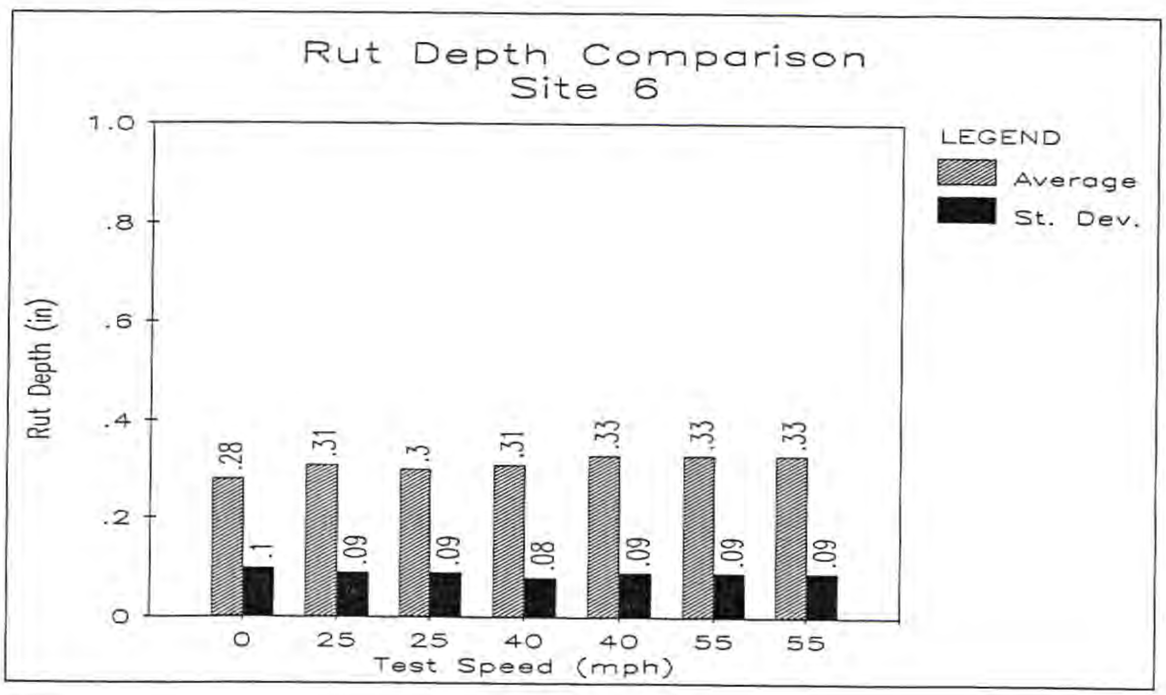


Figure 85: Site 6 Rut Depth Averages

RUT012: Rut Depth Plot Program

Demonstration Project 72; Site # 6
Highway: 1083 From 117.00 -0.19 to 117.00 + 0.00

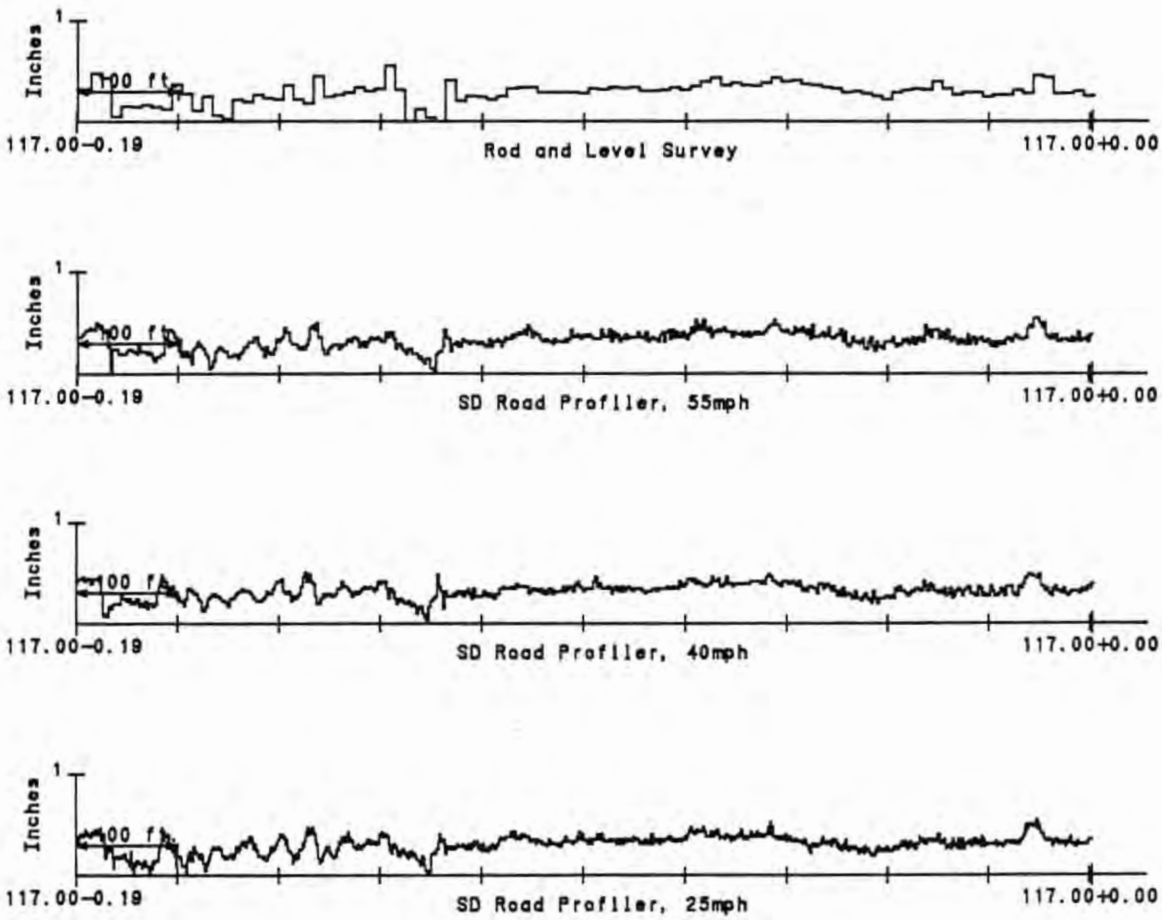


Figure 86: Site 6 Rut Depth Plots

8.7 Site 7

Site 7 is on US14 approximately three miles east of Pierre (Figure 87). The 7.5" portland cement concrete pavement was placed in 1980. Joints occur at fifteen foot intervals, and are not doweled. The surface is transversely tined 0.1 inched deep at one inch spacing (Figure 88). When tested, little wear was evident in the wheelpaths.

Except for a long vertical curve and features corresponding to the slab length, Site 7 profiles were very flat. The Road Profiler's measurement of the vertical curve, with very long wavelength, was different from the manual survey (Figure 89).

Profiles measured by the Road Profiler also show significantly more profile corresponding to slab length (Figure 90). The Road Profiler's power spectral density plots (Figure 91) show much stronger peaks at 4, 8, 16, and 32 feet, which are the wavelengths nearest to multiples and submultiples of the joint spacing. More recent measurements on this highway show that its profile changes with temperature, both seasonally and daily. Slab curl and changes in aggregate interlock at the joints apparently produce the profile variations. For this evaluation, manual survey and Road Profiler measurements were separated by ten days. It was not possible to repeat the surveys on the same day.

Because of increased slab-related roughness, roughness indexes obtained from the Road Profiler surveys are more severe than those obtained by manual survey (Figure 92). The manual survey's IRI is 1.28 mm/m compared to 1.40-1.48 mm/m for the Road Profiler. Similarly, the PSIs of the Road Profiler profiles are generally lower than that of the manual survey.

The manual survey at site 7 shows little wear in the wheelpaths (Figure 93). The Road Profiler measurements occasionally show rut depth, but at very small levels (Figure 94).

SITE DATA
Site 7

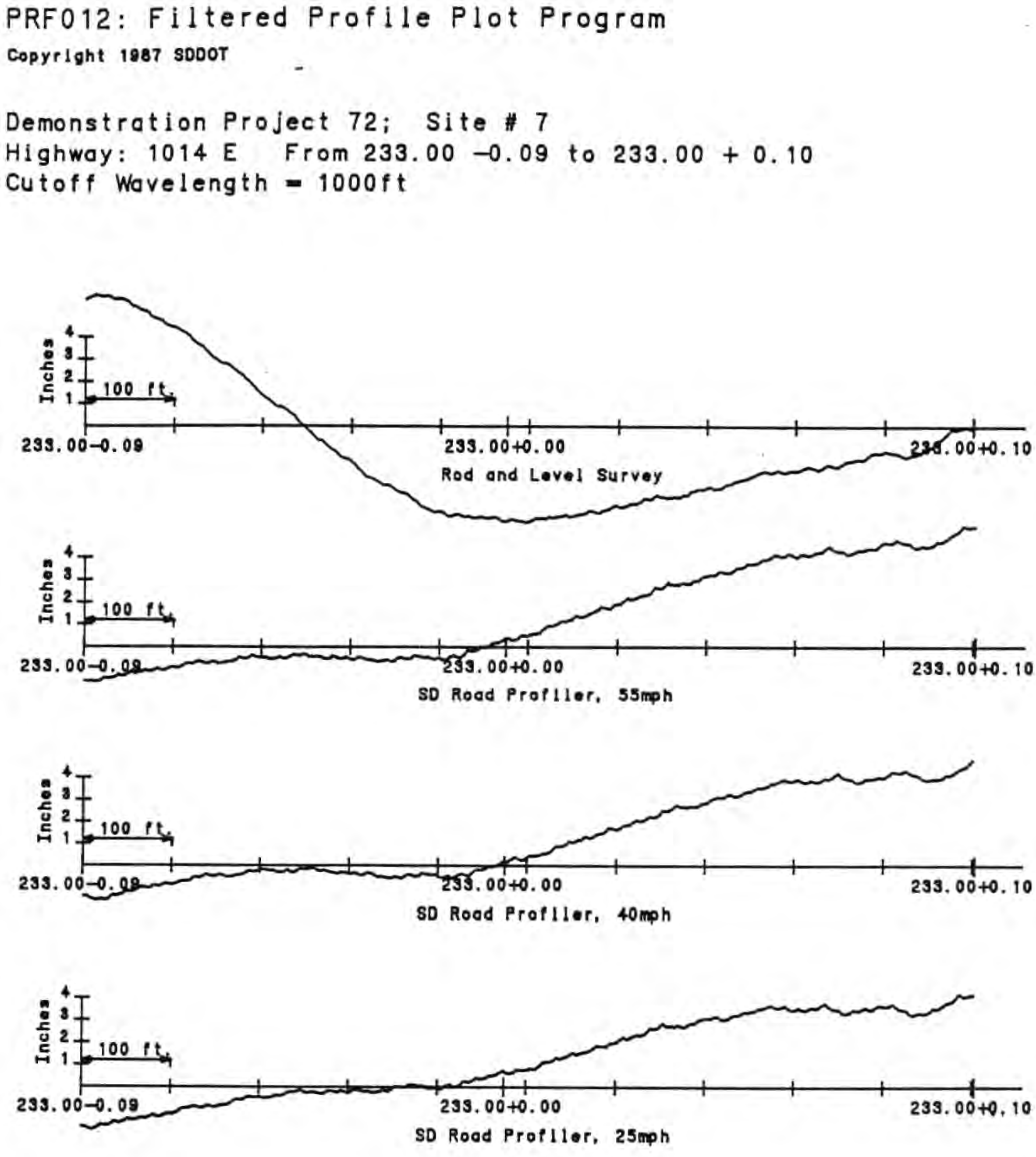


Figure 89: Site 7 Profiles, 1000' Cutoff

Figure 87: Site 7

Figure 88: Site 7 Pavement Texture

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 7
Highway: 1014 E   From 233.00 -0.10 to 233.00 + 0.10
Cutoff Wavelength = 200ft

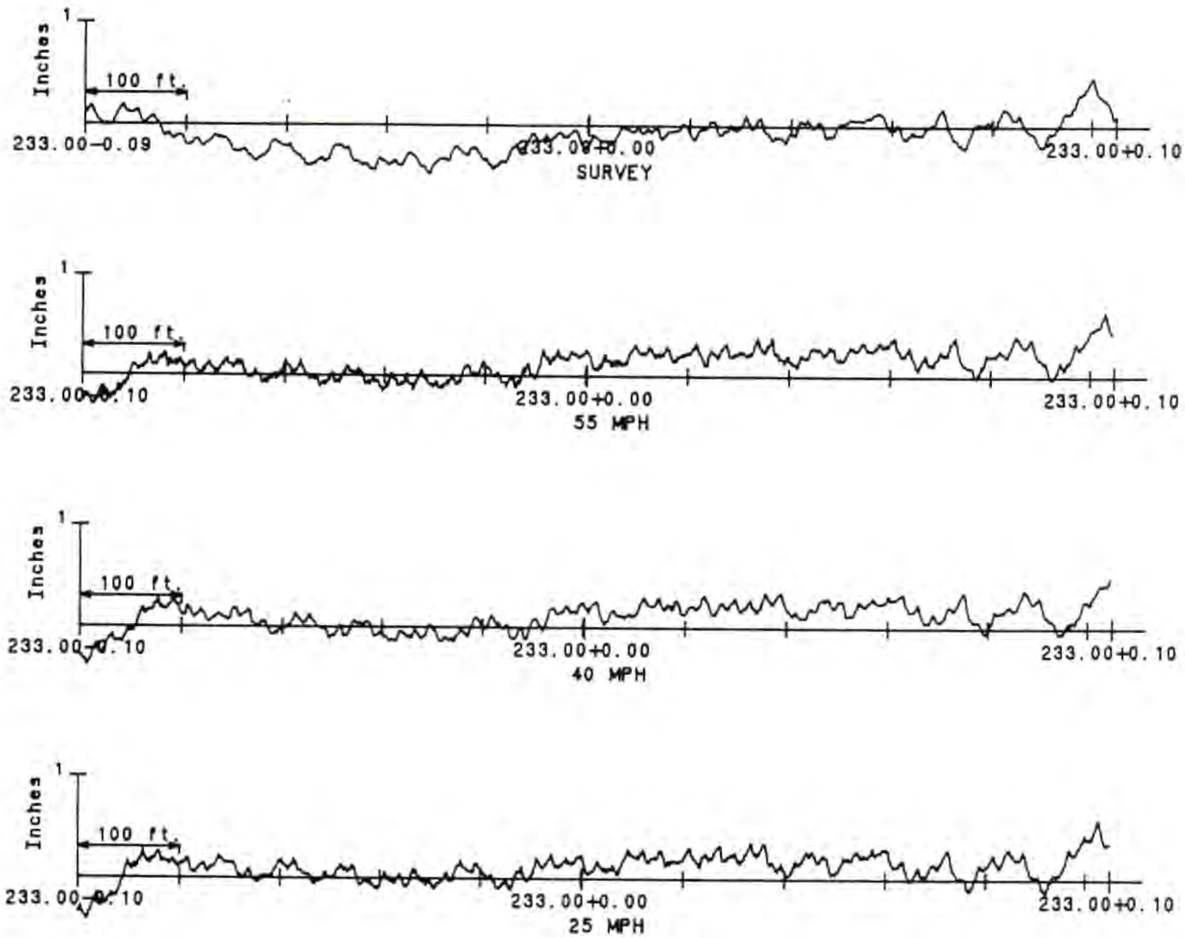


Figure 90: Site 7 Profiles, 200' Cutoff

SITE DATA
Site 7

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site # 7
Highway: 1014 E   From 233.00 –0.10 to 233.00 + 0.10

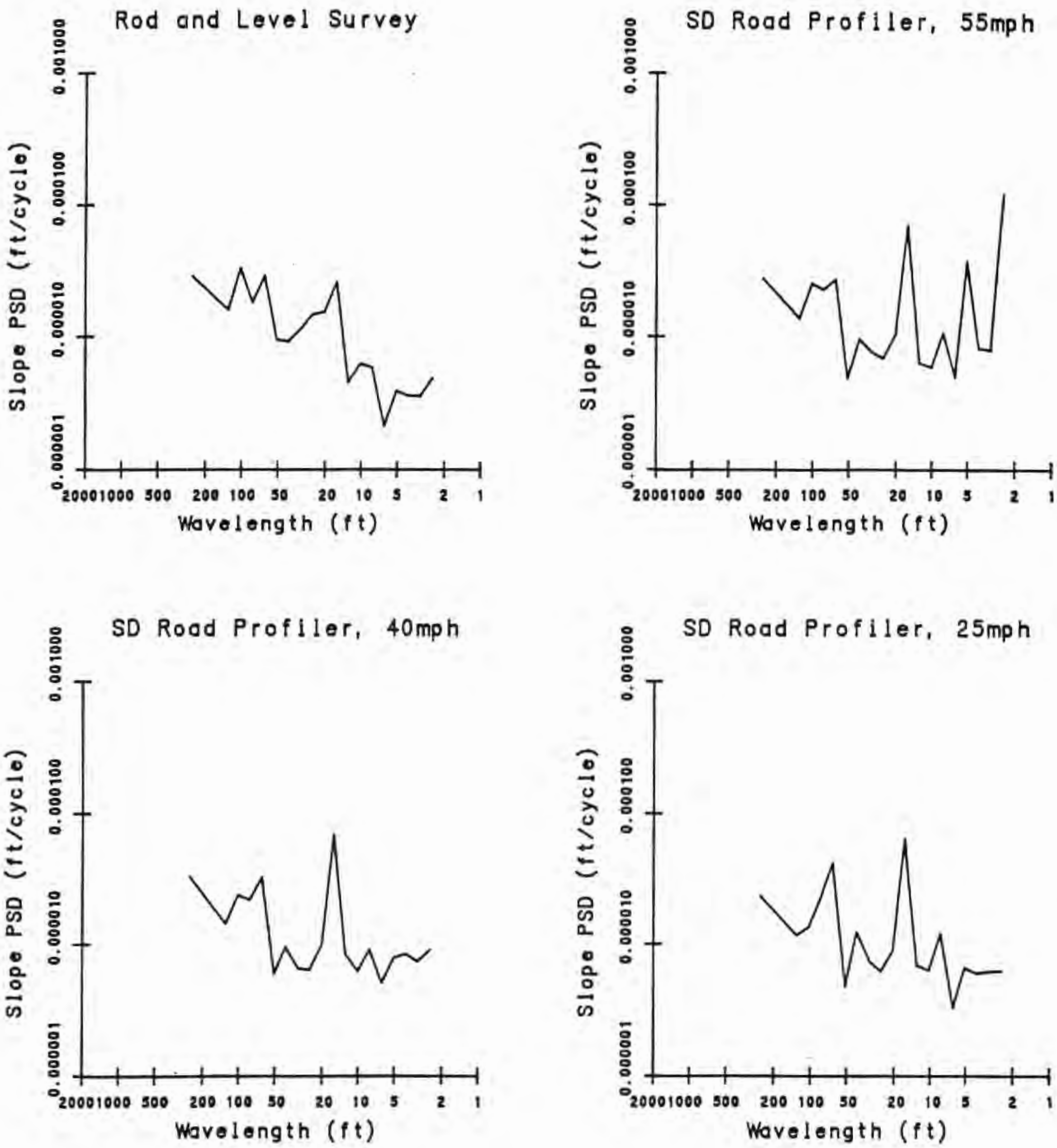


Figure 91: Site 7 Spectral Analysis Plots

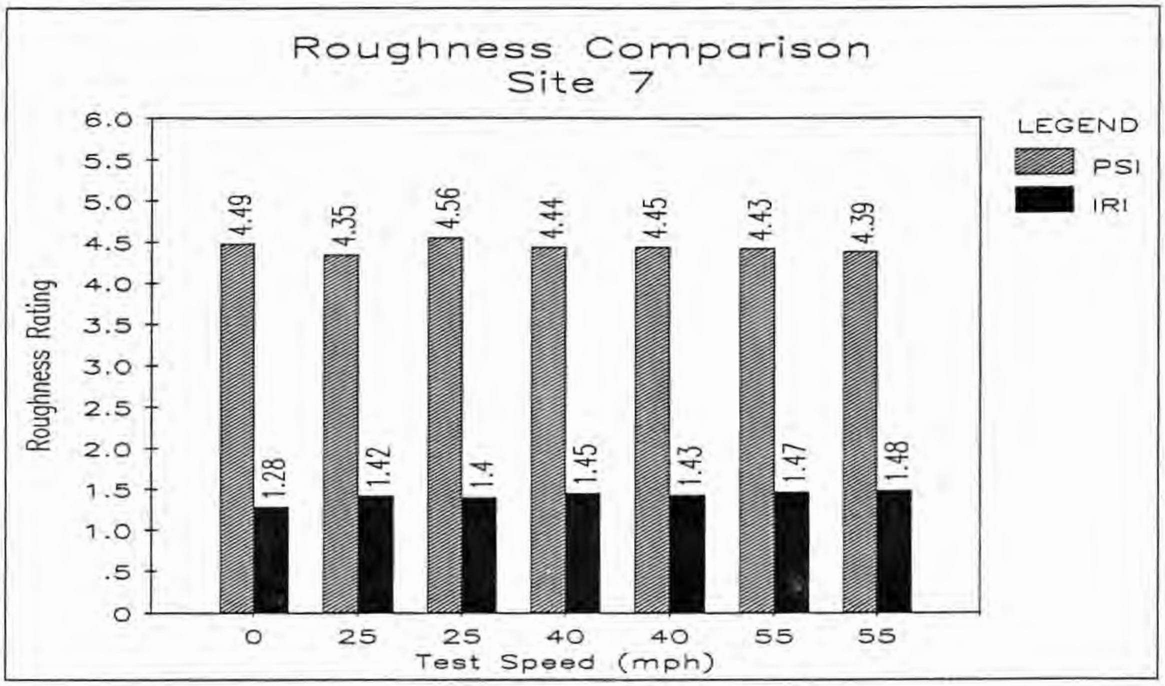


Figure 92: Site 7 Roughness Ratings

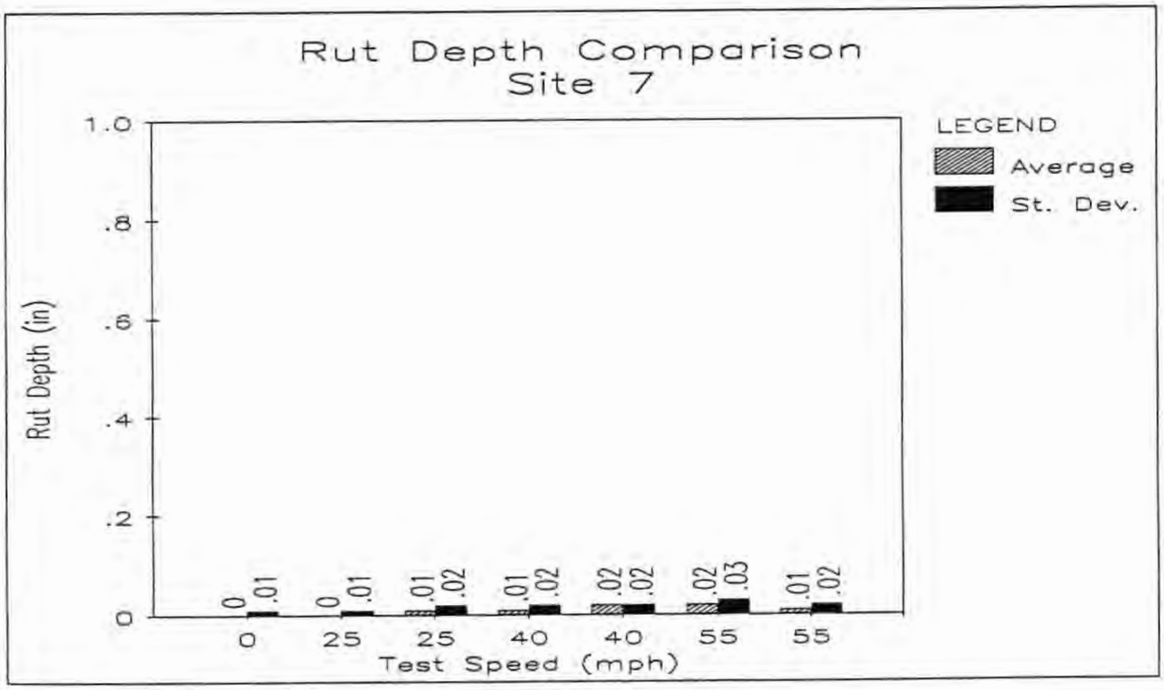


Figure 93: Site 7 Rut Depth Averages

SITE DATA
Site 7

RUT012: Rut Depth Plot Program
Copyright 1987 SDDOT

Demonstration Project 72; Site # 7
Highway: 1014 E From 233.00 -0.09 to 233.00 + 0.10

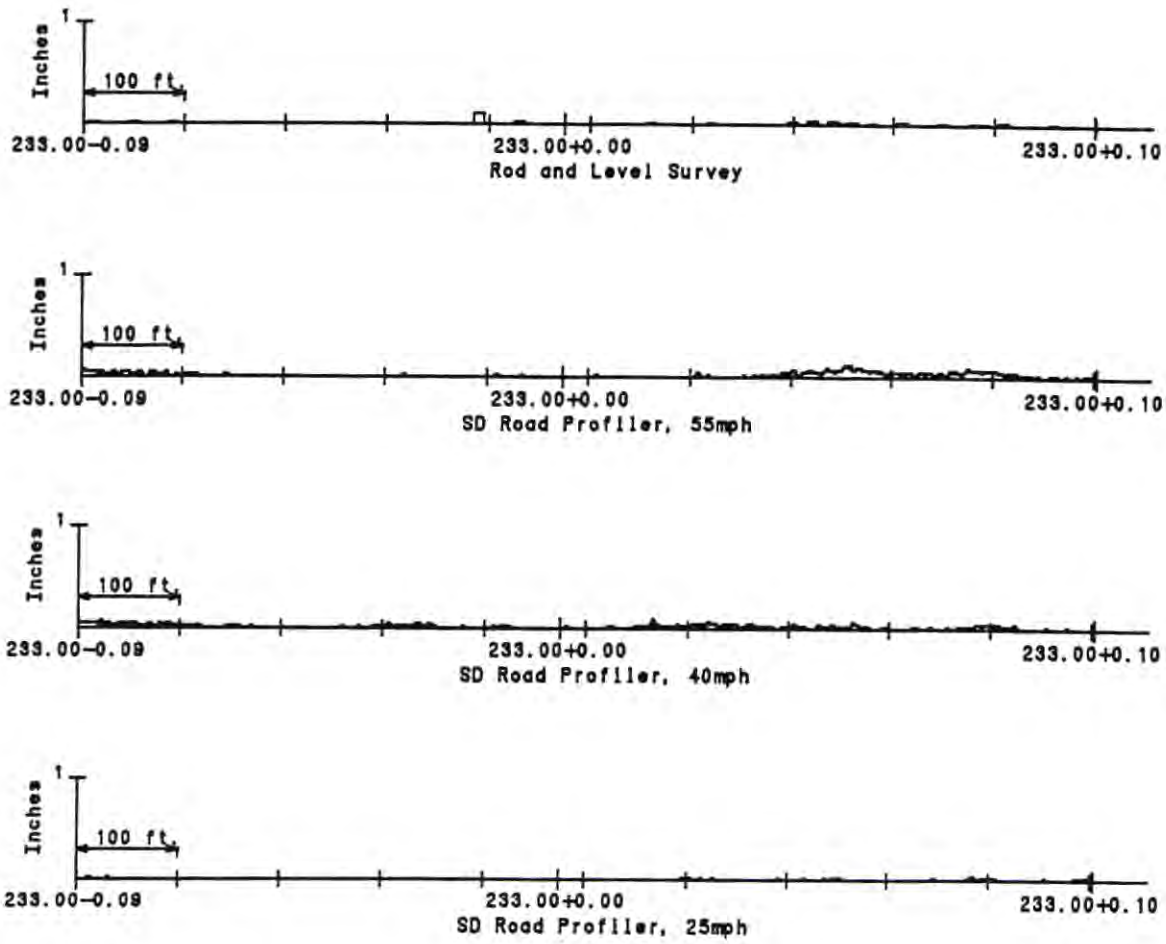


Figure 94: Site 7 Rut Depth Plots

8.8 Site 8

Site 8 is on US14 approximately five miles east of Pierre (Figure 95). Like Site 7, its pavement consists of 7.5" portland cement concrete on 4.5" of gravel cushion. The pavement has a 15' joint spacing, and is undowelled. It is transversely tined to a depth of 0.1" on one inch spacing (Figure 96). When tested, slight wear was evident in the wheelpaths.

The differences between manual survey and Road Profiler profiles were similar to those at Site 7. Profile plots (Figures 97 and 98) show more joint-related features in the Road Profiler profiles than in the manual survey. Power spectral density plots reflect these differences with stronger peaks at 4,8,16, and 32 feet (Figure 99).

As at Site 7, the profiles measured by the Road Profiler have more severe roughness ratings than does the manually surveyed profile. The manual survey's IRI and PSI are 1.48 and 4.51, respectively, compared to the Road Profiler's index ranges of 1.57-1.67 and 4.05-4.39. As at Site 7, the cause of these differences is thought to reflect pavement changes between the manual and Road Profiler surveys.

Both the manual and Road Profiler surveys detected slight wear in the wheelpaths (Figure 102). The Road Profiler's average rut depths ranged from 0.07-0.09 inches, compared to the manual survey's average depth of 0.05 inches (Figure 101). Standard deviations were nearly identical for all surveys.

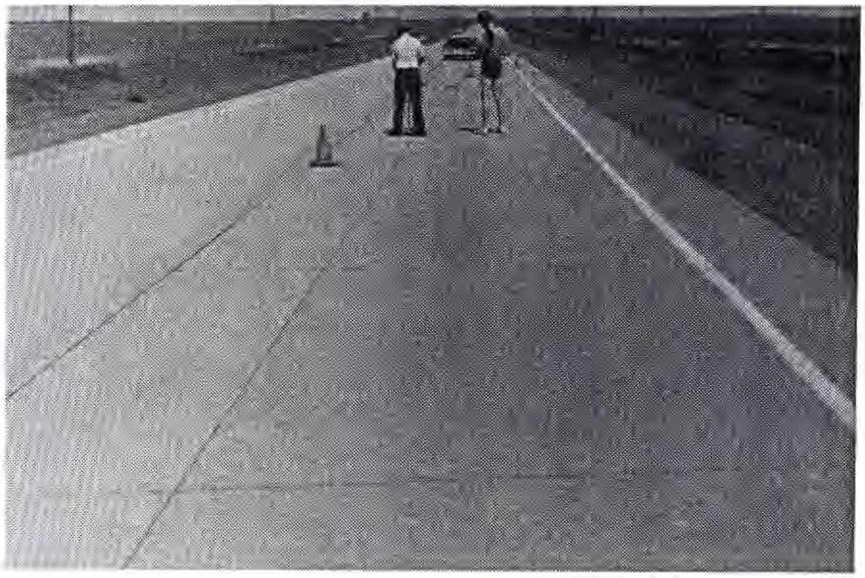


Figure 95: Site 8

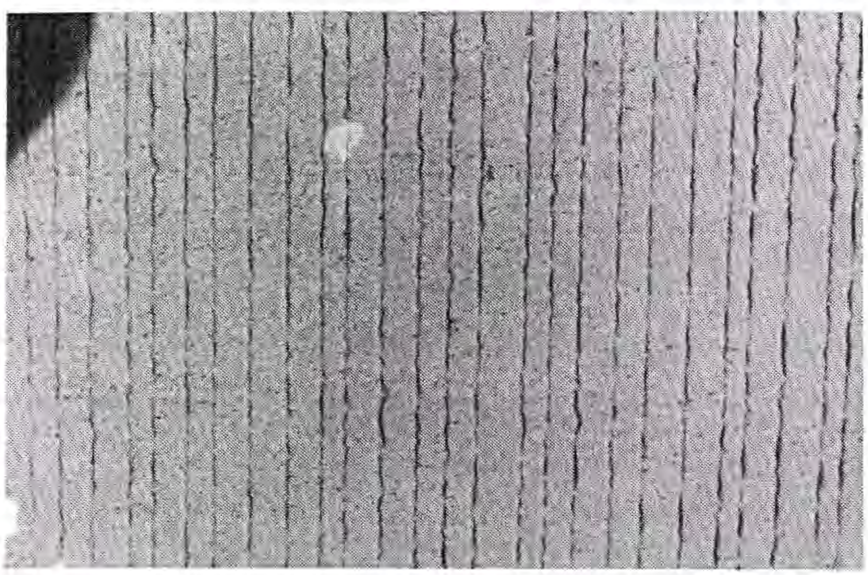


Figure 96: Site 8 Pavement Texture

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 8
Highway: 1014   From 238.00 + 0.00 to 238.00 + 0.19
Cutoff Wavelength = 1000ft

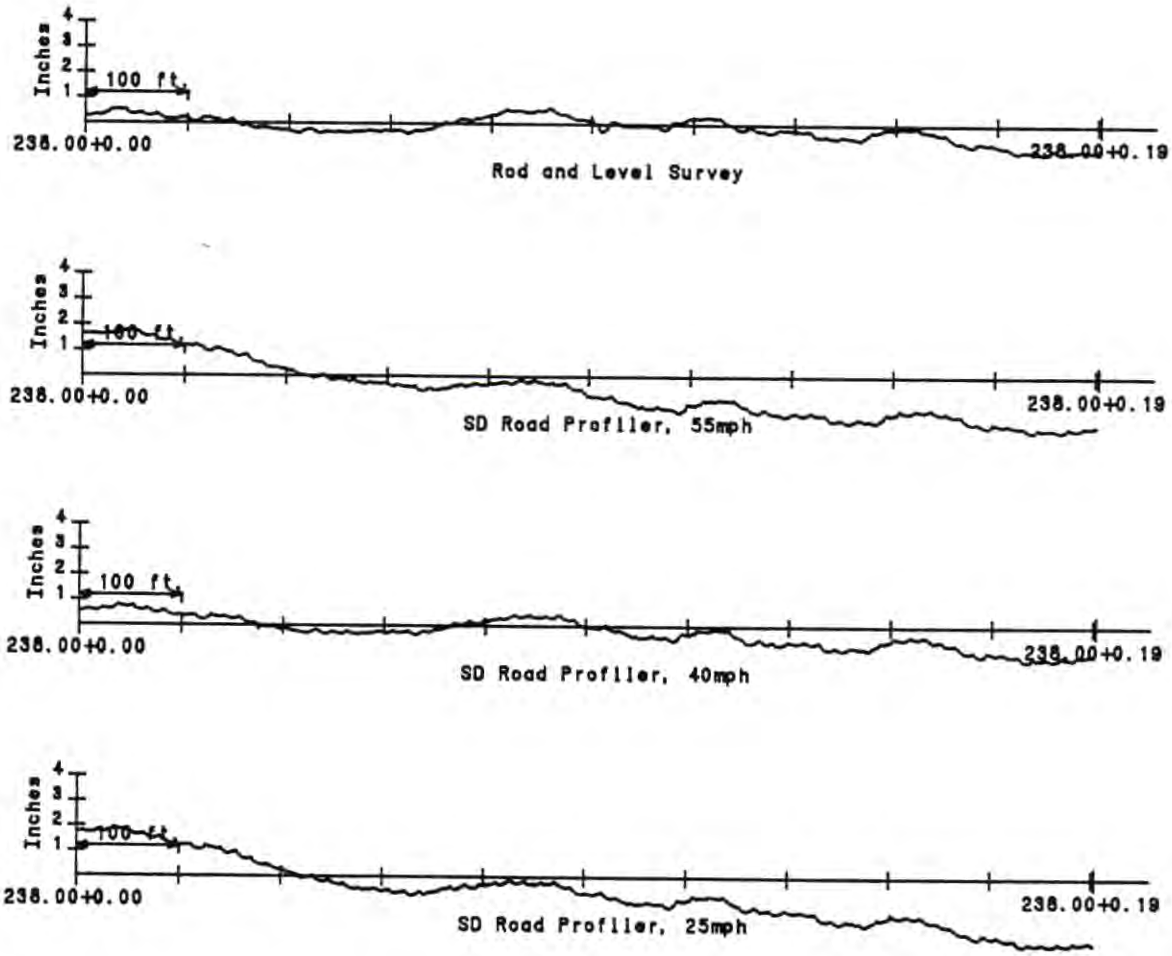


Figure 97: Site 8 Profiles, 1000′ Cutoff

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 8
Highway: 1014 From 238.00 + 0.00 to 238.00 + 0.19
Cutoff Wavelength = 200ft

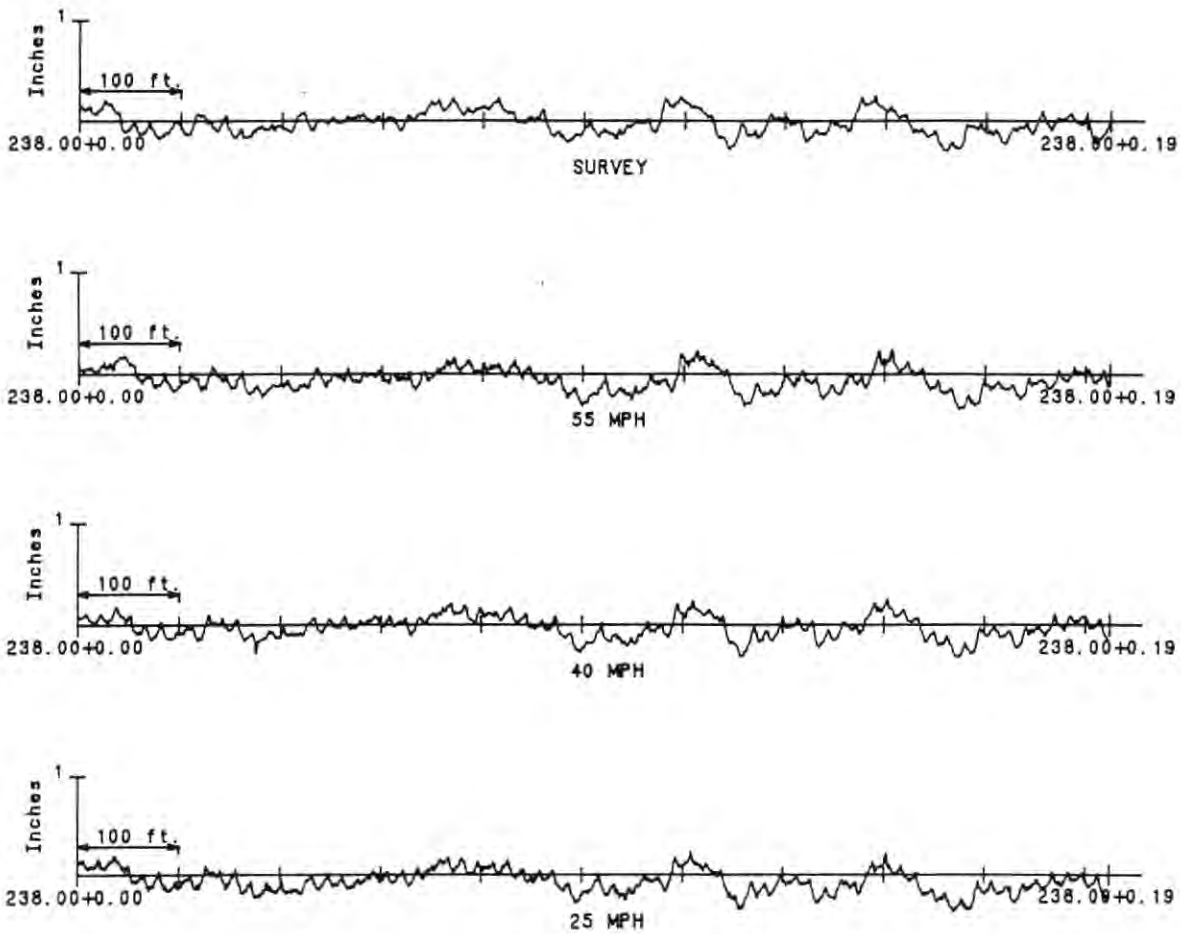


Figure 98: Site 8 Profiles, 200′ Cutoff

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site # 8
Highway: 1014 From 238.00 + 0.00 to 238.00 + 0.19

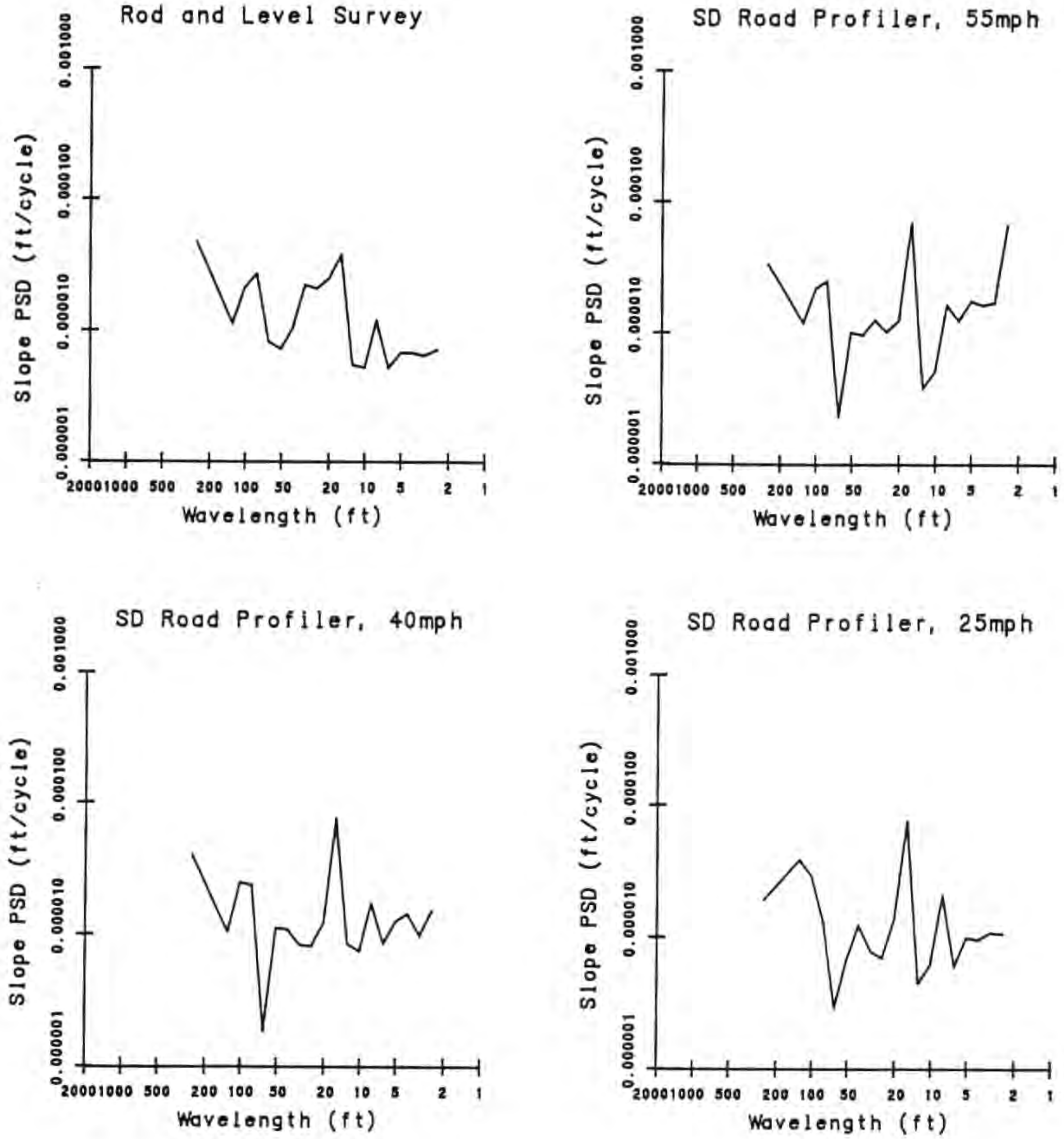


Figure 99: Site 8 Spectral Analysis Plots

SITE DATA
Site 8

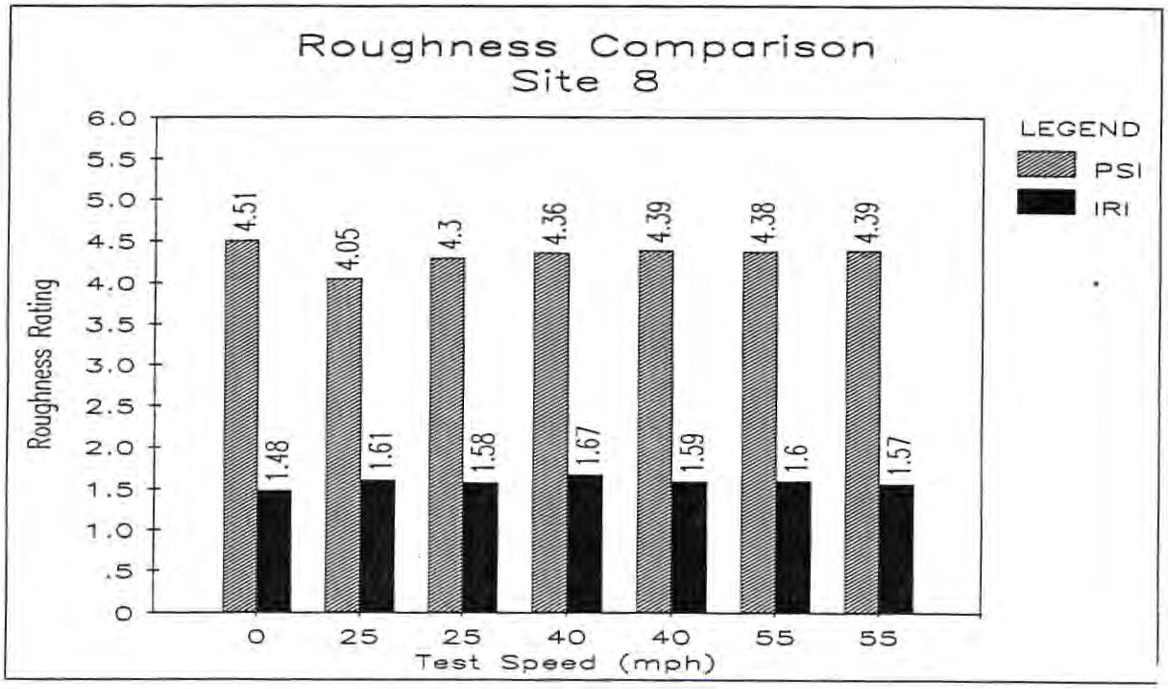


Figure 100: Site 8 Roughness Ratings

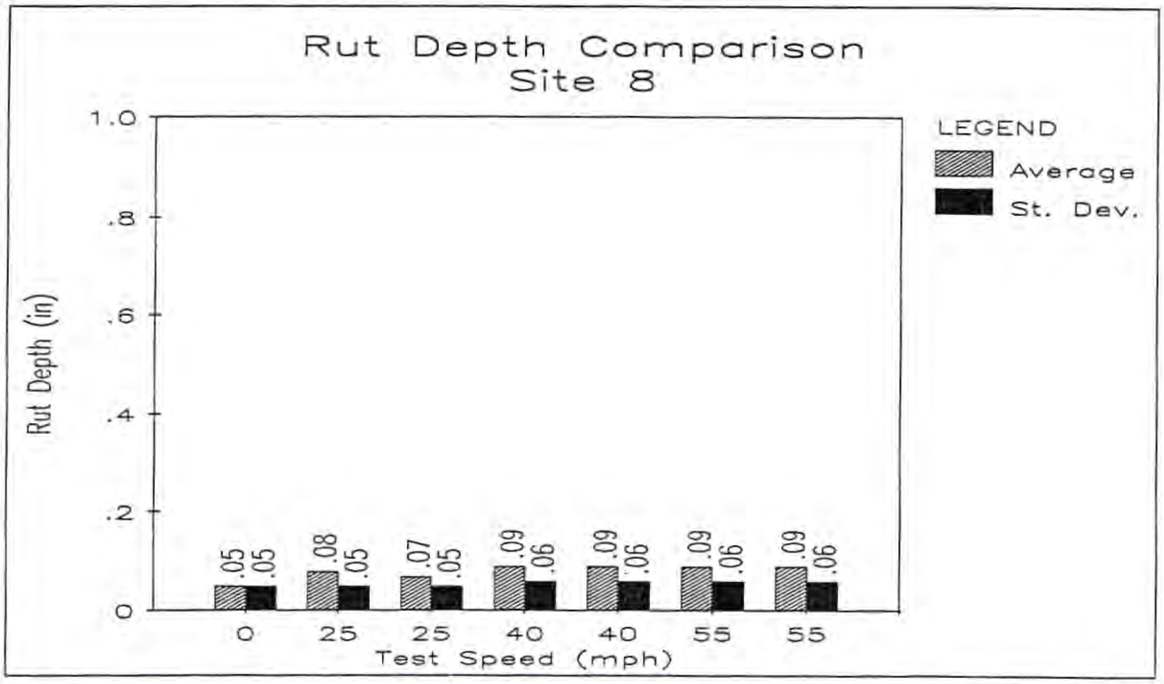


Figure 101: Site 8 Rut Depth Averages

RUT012: Rut Depth Plot Program

Demonstration Project 72; Site # 8
Highway: 1014 From 238.00 + 0.00 to 238.00 + 0.19

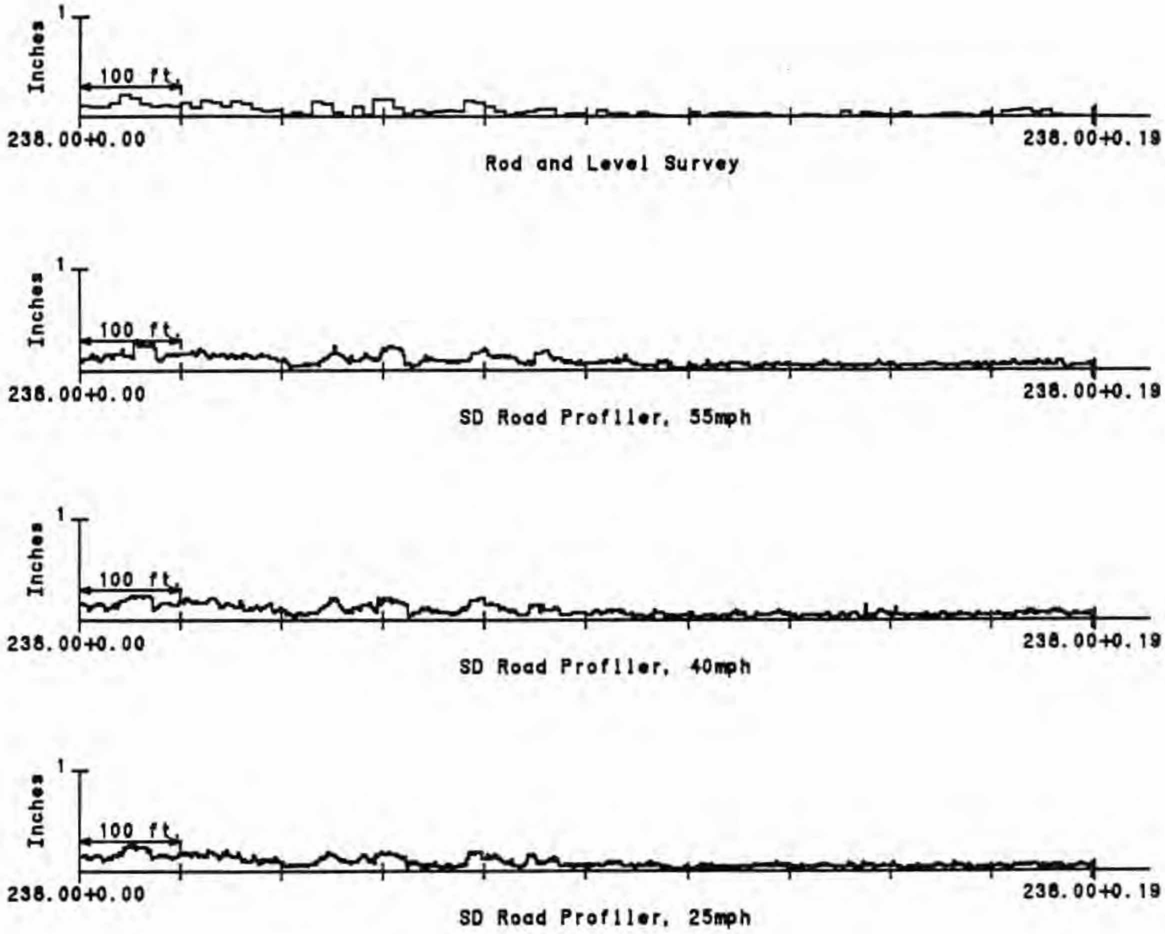


Figure 102: Site 8 Rut Depth Plots

8.9 Site 9

Site 9 is on Interstate 90, approximately 35 miles south of Pierre (Figure 103). Its surface consists of eight inch continuously reinforced concrete pavement on a lime treated base three inches thick. The pavement is transversely cracked, as is typical of CRCP. It is not tined (Figure 104). When tested, the wheelpaths were worn slightly.

The long wavelength profile plots (Figure 105) illustrate the Road Profiler's attenuation of the vertical curve at Site 9. The plots with 200 foot cutoff (Figure 106) agree more closely. The 40 mph profile contains features approximately four feet long; these are much more evident than in any other profile. Power spectral density plots also show this difference (Figure 107).

This wavelength corresponds to the spacing of transverse reinforcing steel in the pavement, suggesting that this profile's sampling points may coincide with steel locations. If this is the case, these profiles illustrate the effect of sampling at one foot intervals. The Road Profiler may or may not detect short irregularities, depending where they fall relative to the measurement locations.

The IRIs of the 40mph profiles are correspondingly worse than the other profiles' (Figure 108). Less variation is evident in the Present Serviceability Indexes.

The Road Profiler measured average rut depth of 0.09 to 0.12 inches, compared by 0.09 inches for the manual survey (Figure 109). Measurements were consistent throughout the project's length (Figure 110).

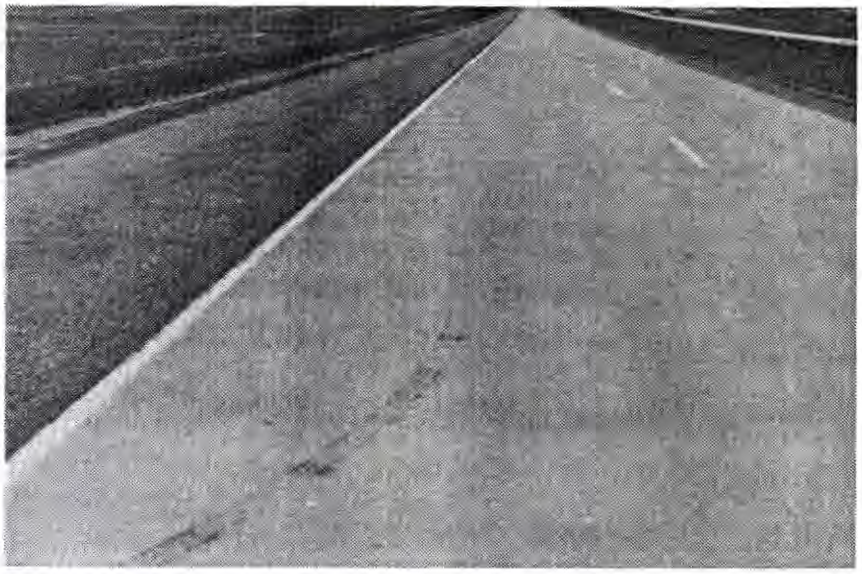


Figure 103: Site 9

Figure 104: Site 9 Pavement Texture

SITE DATA
Site 9

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 9
Highway: 1090 W From 218.00 + 0.00 to 218.00 + 0.19
Cutoff Wavelength = 1000ft

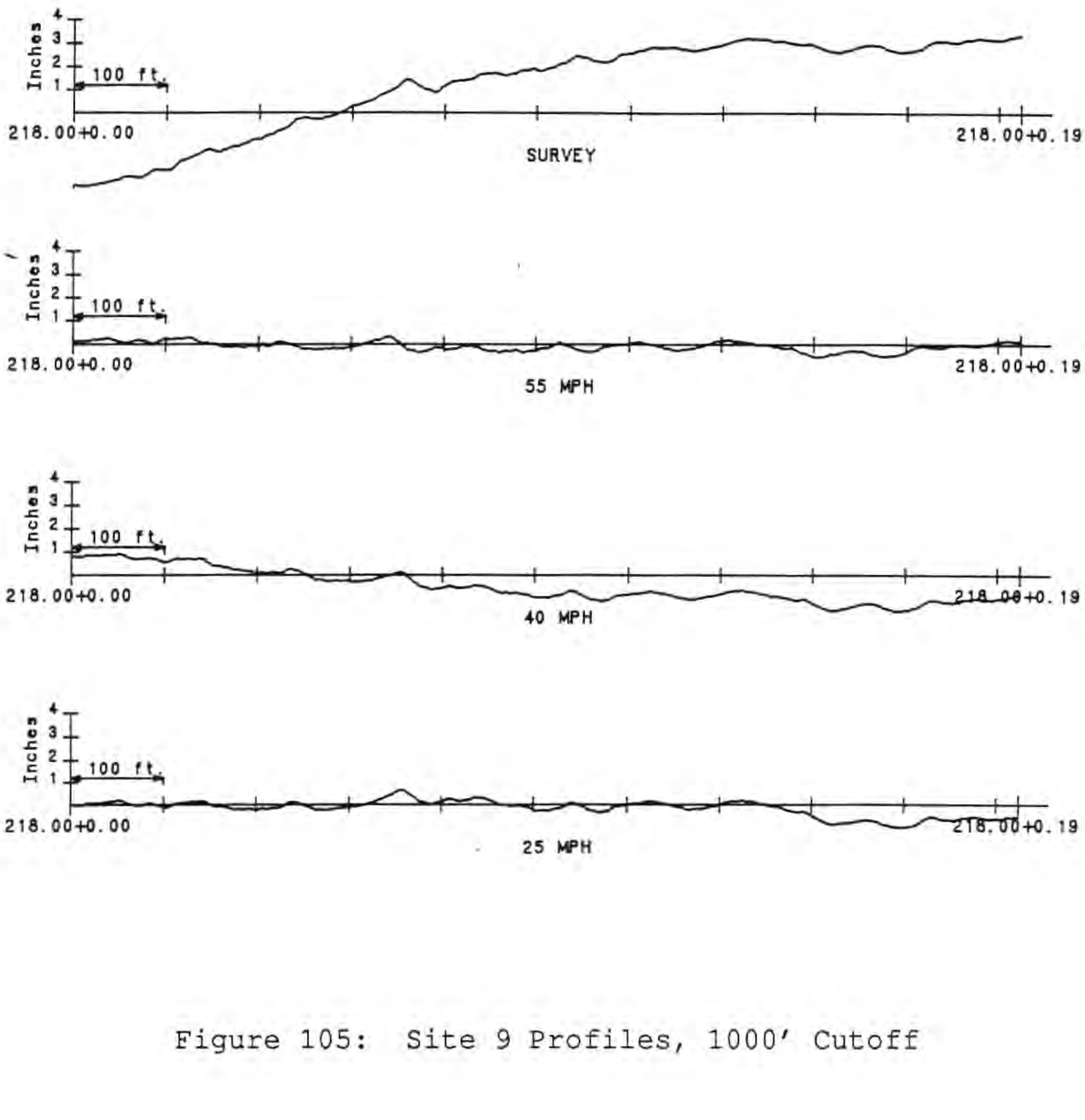


Figure 105: Site 9 Profiles, 1000′ Cutoff

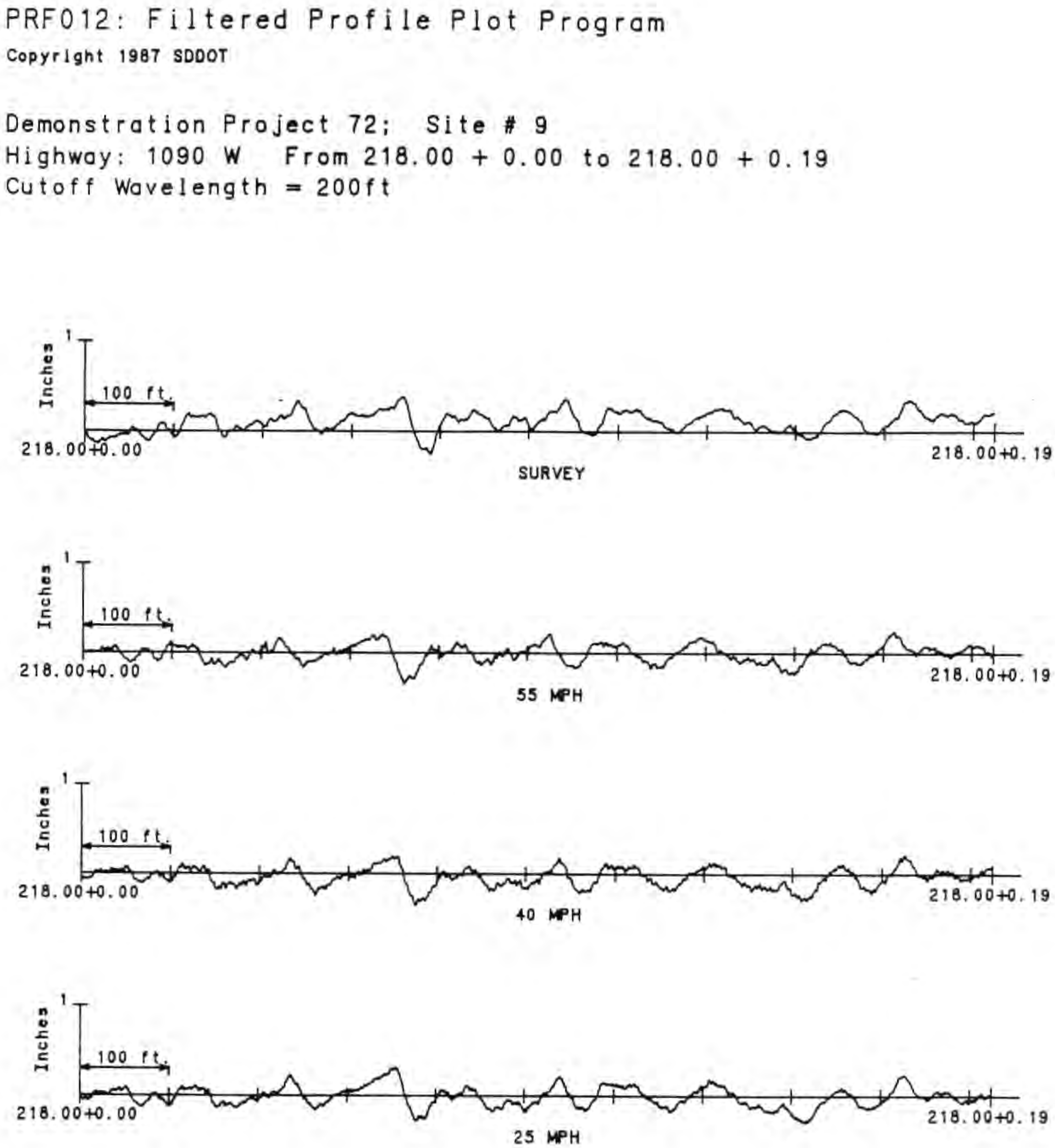


Figure 106: Site 9 Profiles, 200′ Cutoff

SITE DATA
Site 9

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

DEMO 72 SITE #9
Highway: 1090 W   From 218.00 + 0.00 to 218.00 + 0.19

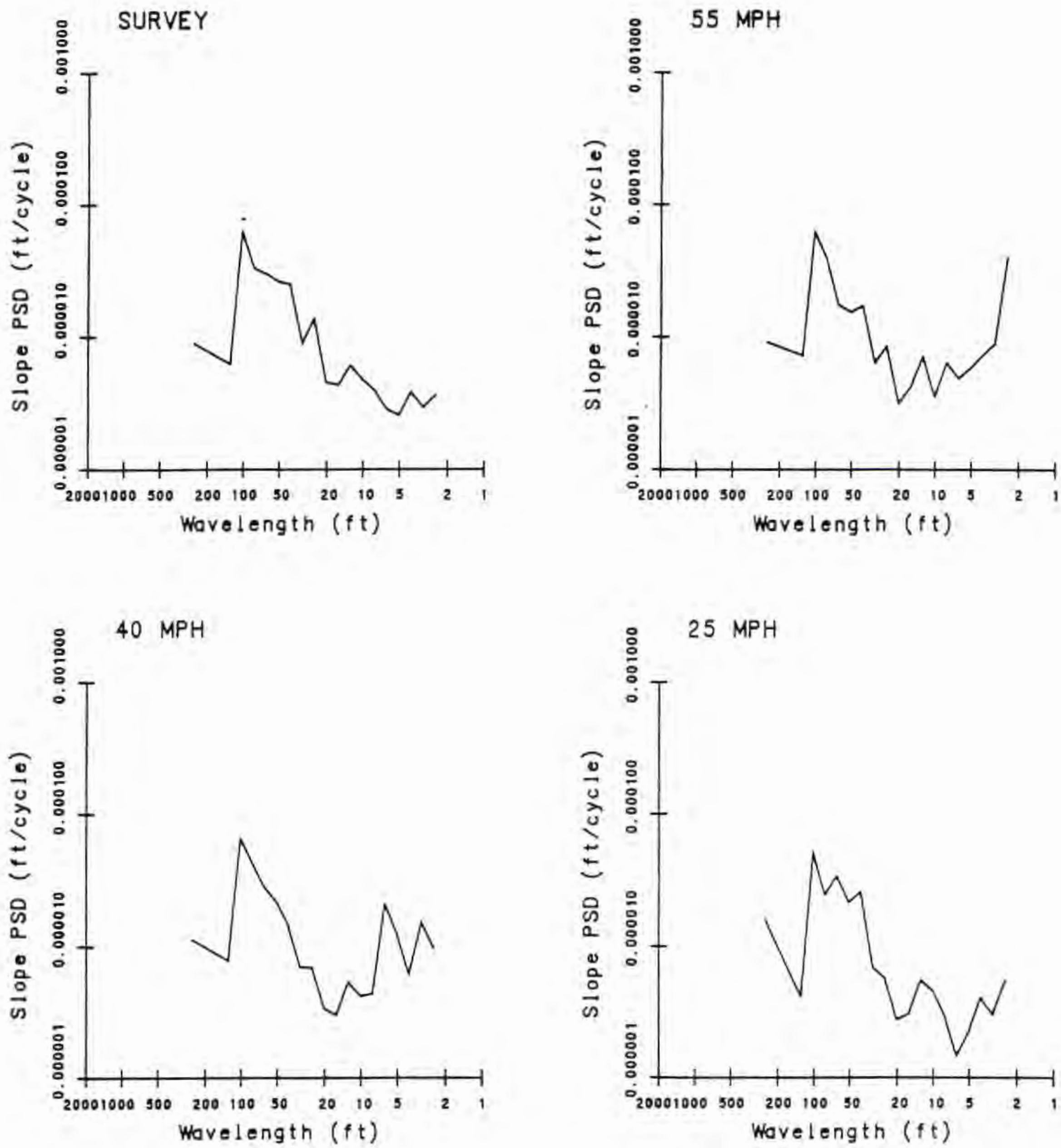


Figure 107: Site 9 Spectral Analysis Plots

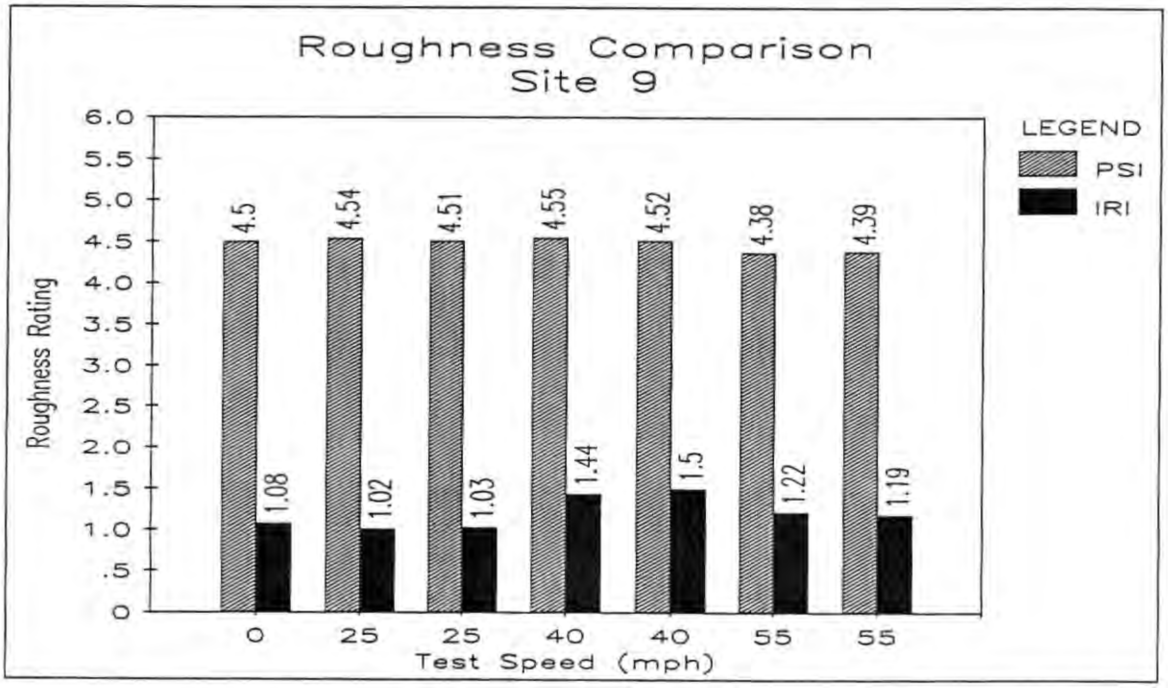


Figure 108: Site 9 Roughness Ratings

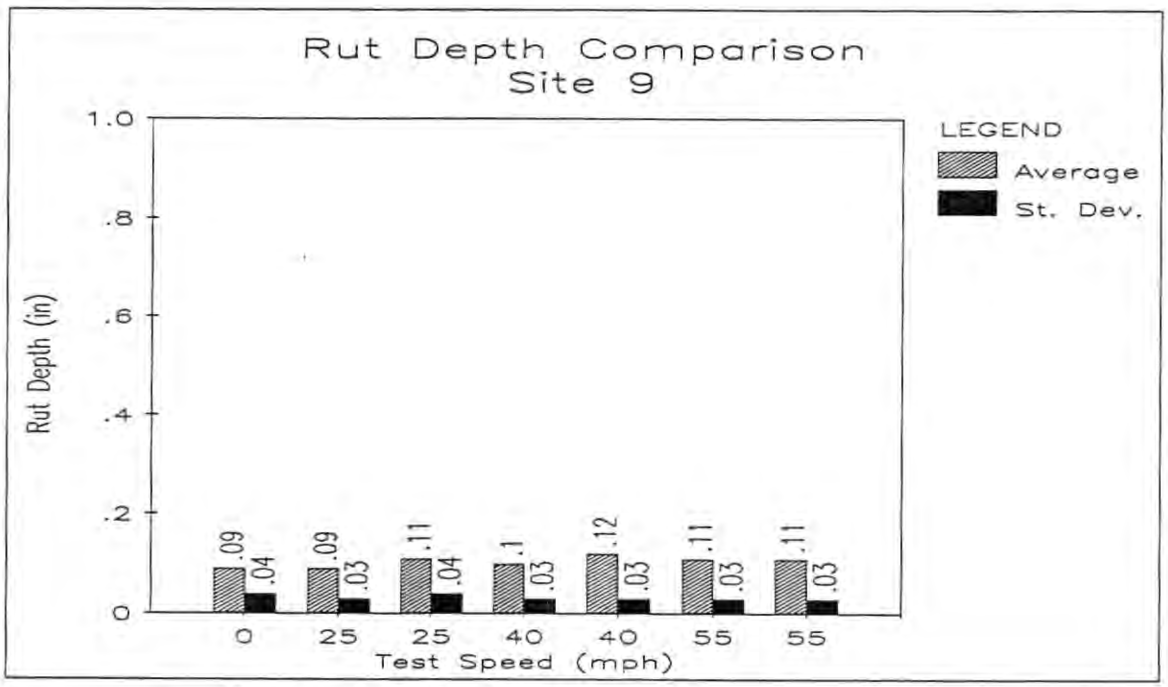
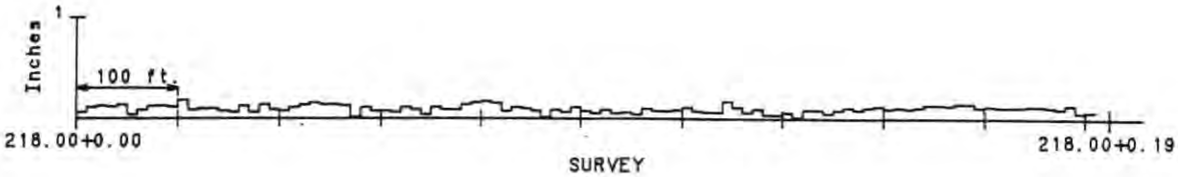


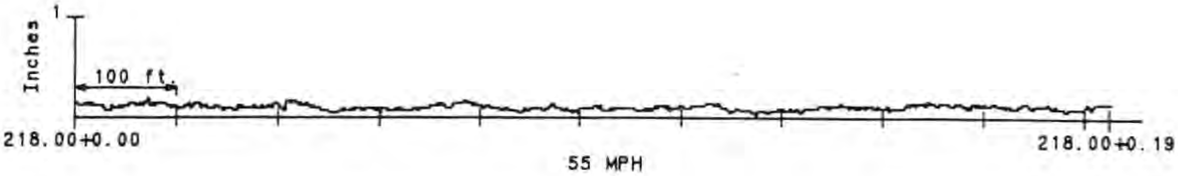
Figure 109: Site 9 Rut Depth Averages

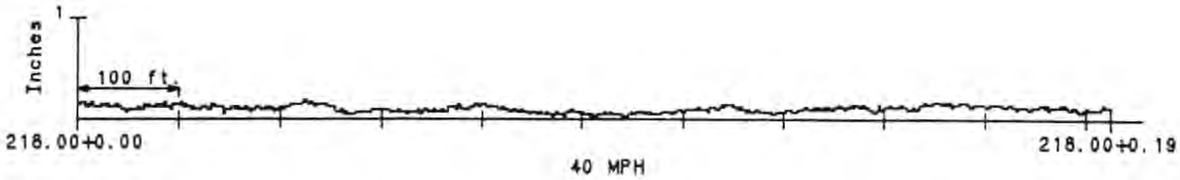
SITE DATA
Site 9

RUT012: Rut Depth Plot Program
Copyright 1987 SDDOT

Demonstration Project 72; Site # 9
Highway: 1090 W From 218.00 + 0.00 to 218.00 + 0.19







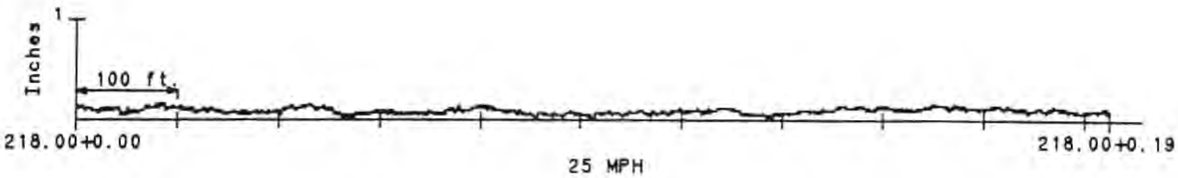


Figure 110: Site 9 Rut Depth Plots

8.10 Site 10

Site 10 is on US14 just west of Pierre (Figure 111). The highway was constructed in 1948 as an asphalt surface treatment atop a 10" gravel base. In 1954, 3" of gravel base were added and a 2" asphalt mat was placed. When tested, the surface was badly distorted and deteriorated. Numerous transverse and longitudinal cracks existed. The highway had lost its cross section because of repeated maintenance patches and seals. Rut depths occasionally exceeded one inch. The texture, which varied with patching, included loose material (Figure 112). Site 10 was reconstructed in 1988.

Severe roughness is evident in the profile plots (Figures 113 and 114). Power spectral density plots (Figure 115) confirm the essential agreement between the Road Profiler profiles and the manual survey.

Although all of the profiles appear to be quite similar, the IRIs for the profiles recorded at 25mph are approximately 0.4 mm/m lower than any of the other surveys' (Figure 116). At this writing, the reason for this difference is unknown. Less variation exists in the Present Serviceability Indexes.

Even though the road's cross section was very irregular, the agreement between manual survey and the Road Profiler's measurements is good (Figure 117). Plots of rut depth measurements show consistency throughout the test section (Figure 118).

Figure 111: Site 10

Figure 112: Site 10 Pavement Texture

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 10
Highway: 1014 From 227.00 + 0.00 to 227.00 + 0.19
Cutoff Wavelength = 1000ft

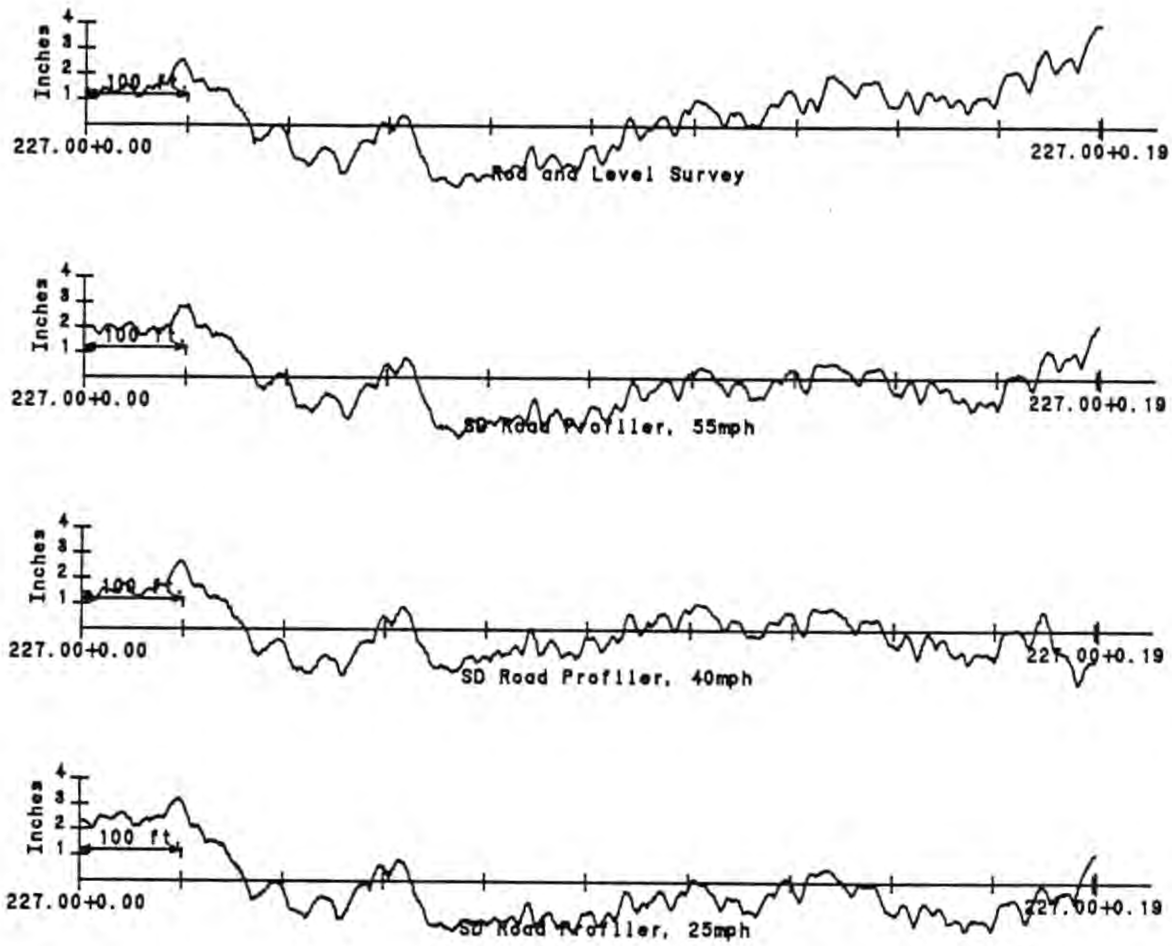


Figure 113: Site 10 Profiles, 1000' Cutoff

PRF012: Filtered Profile Plot Program

Demonstration Project 72; Site # 10
Highway: 1014 From 227.00 + 0.00 to 227.00 + 0.19
Cutoff Wavelength = 200ft

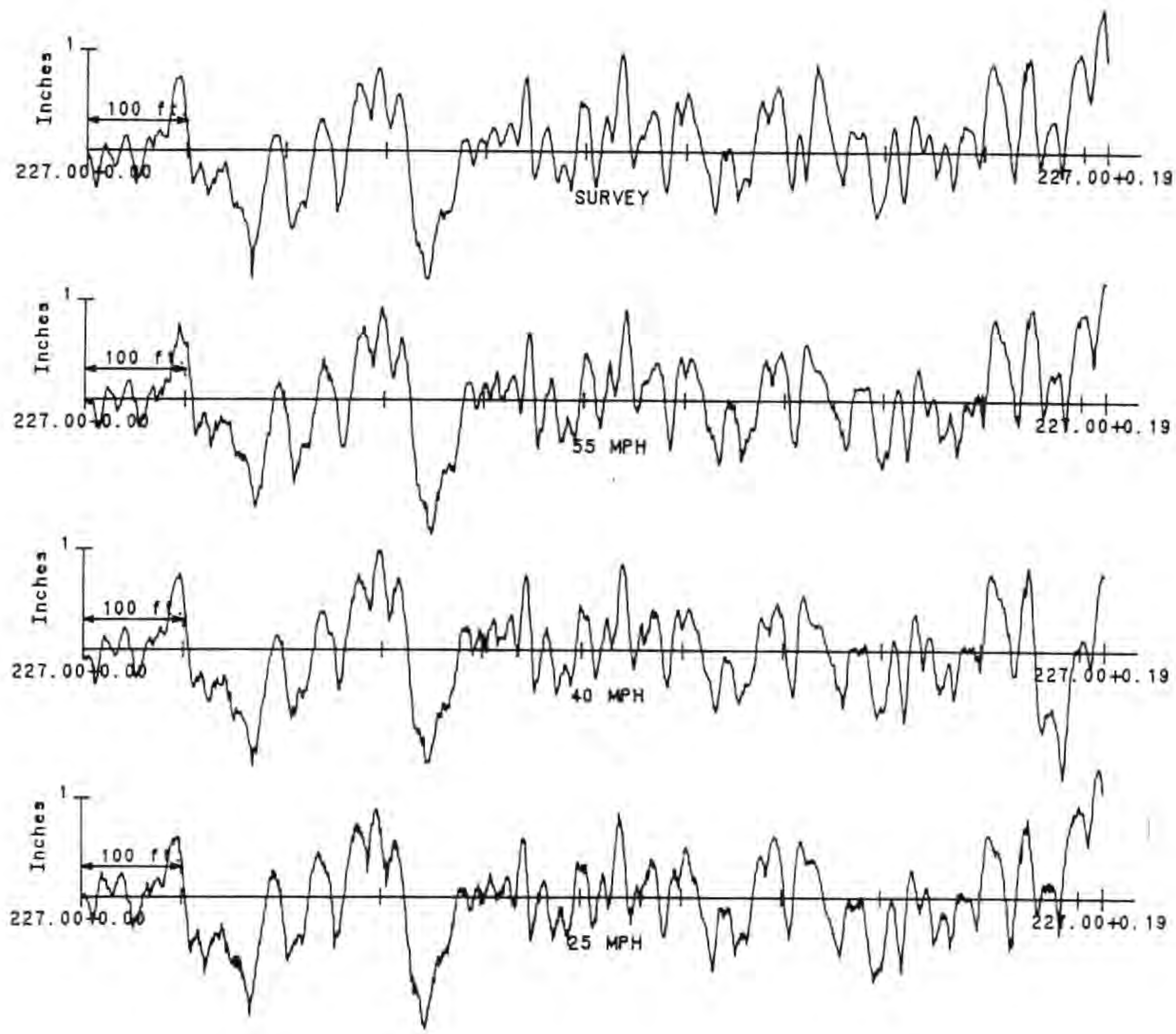


Figure 114: Site 10 Profiles, 200' Cutoff

PRF030: Profile Power Spectral Density
Copyright 1987 SDDOT

Demonstration Project 72; Site # 10
Highway: 1014 From 227.00 + 0.00 to 227.00 + 0.19

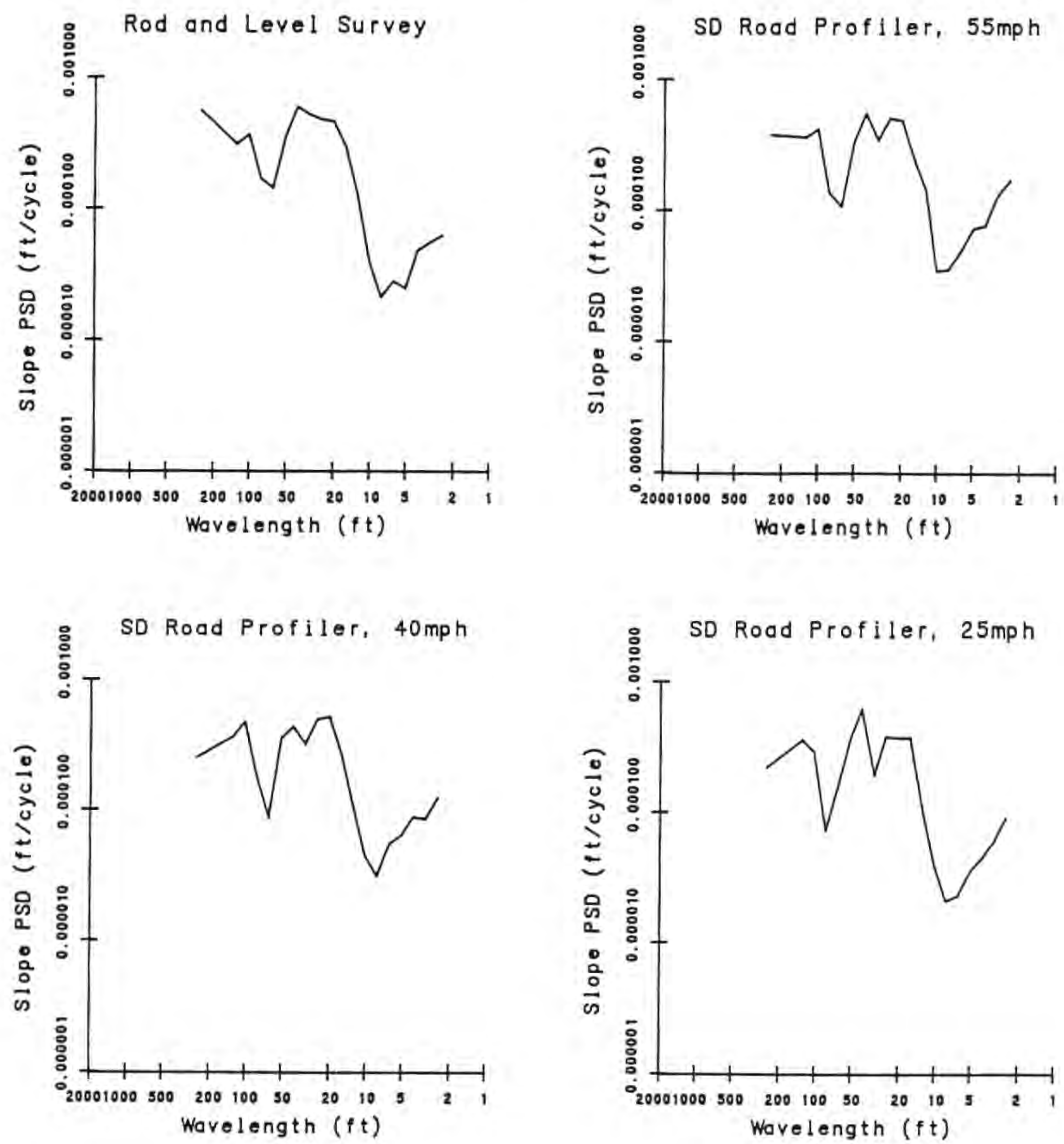


Figure 115: Site 10 Spectral Analysis Plots

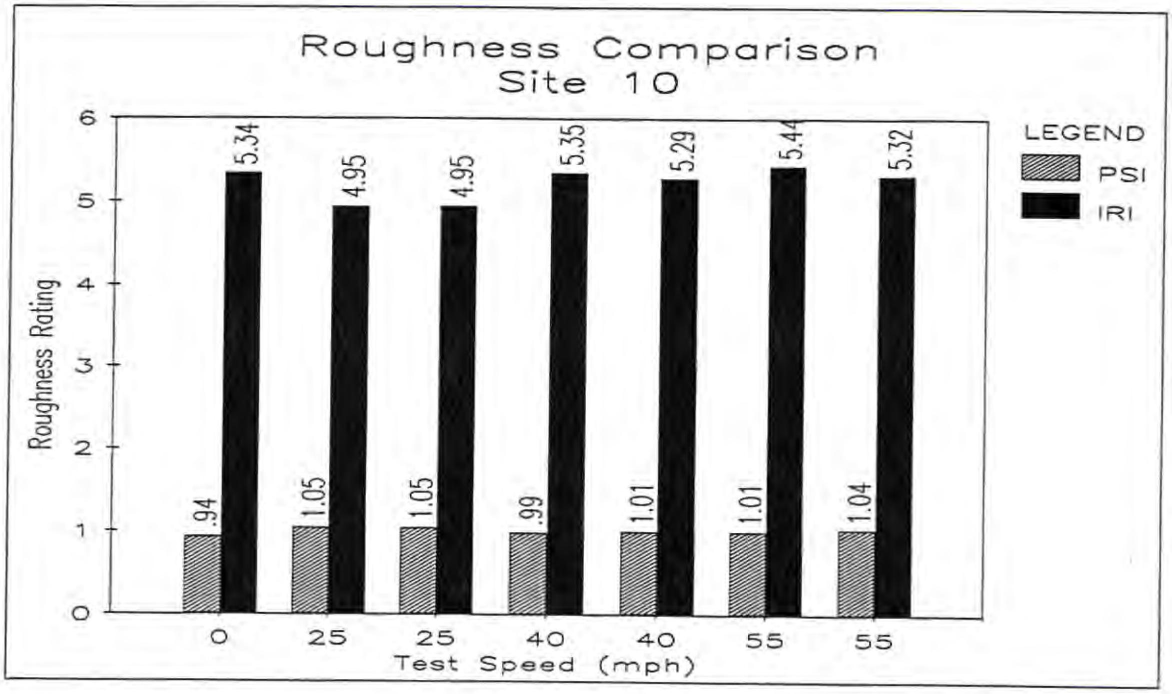


Figure 116: Site 10 Roughness Ratings

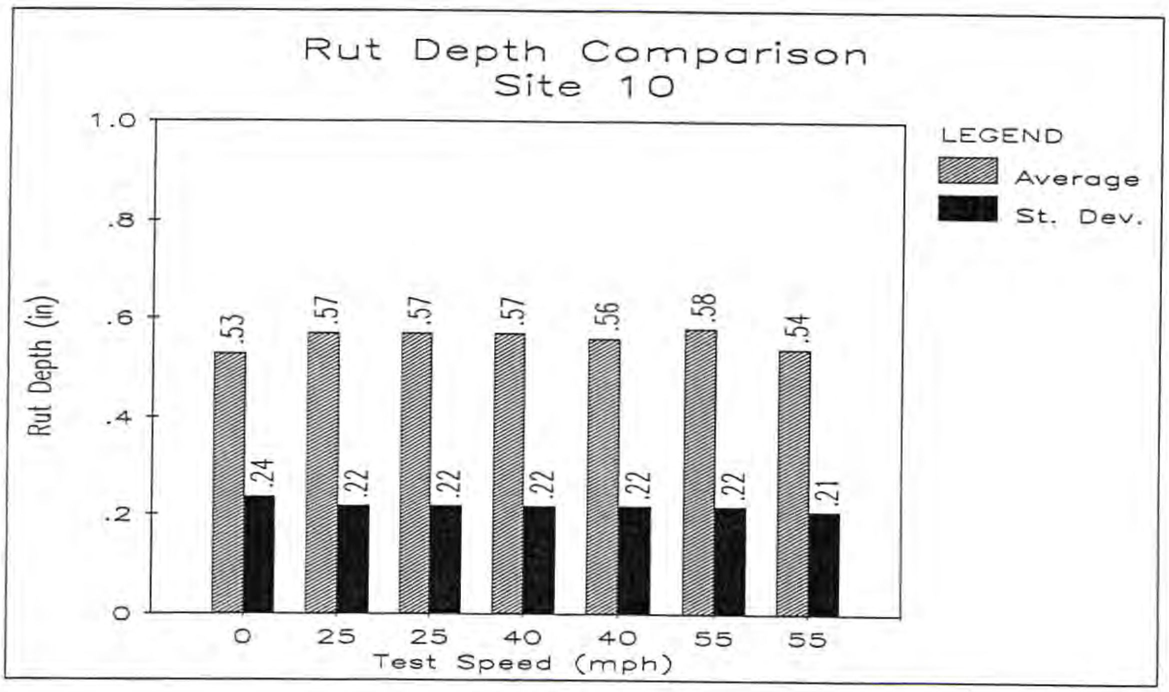


Figure 117: Site 10 Rut Depth Averages

RUT012: Rut Depth Plot Program

Demonstration Project 72; Site # 10
Highway: 1014 From 227.00 + 0.00 to 227.00 + 0.19

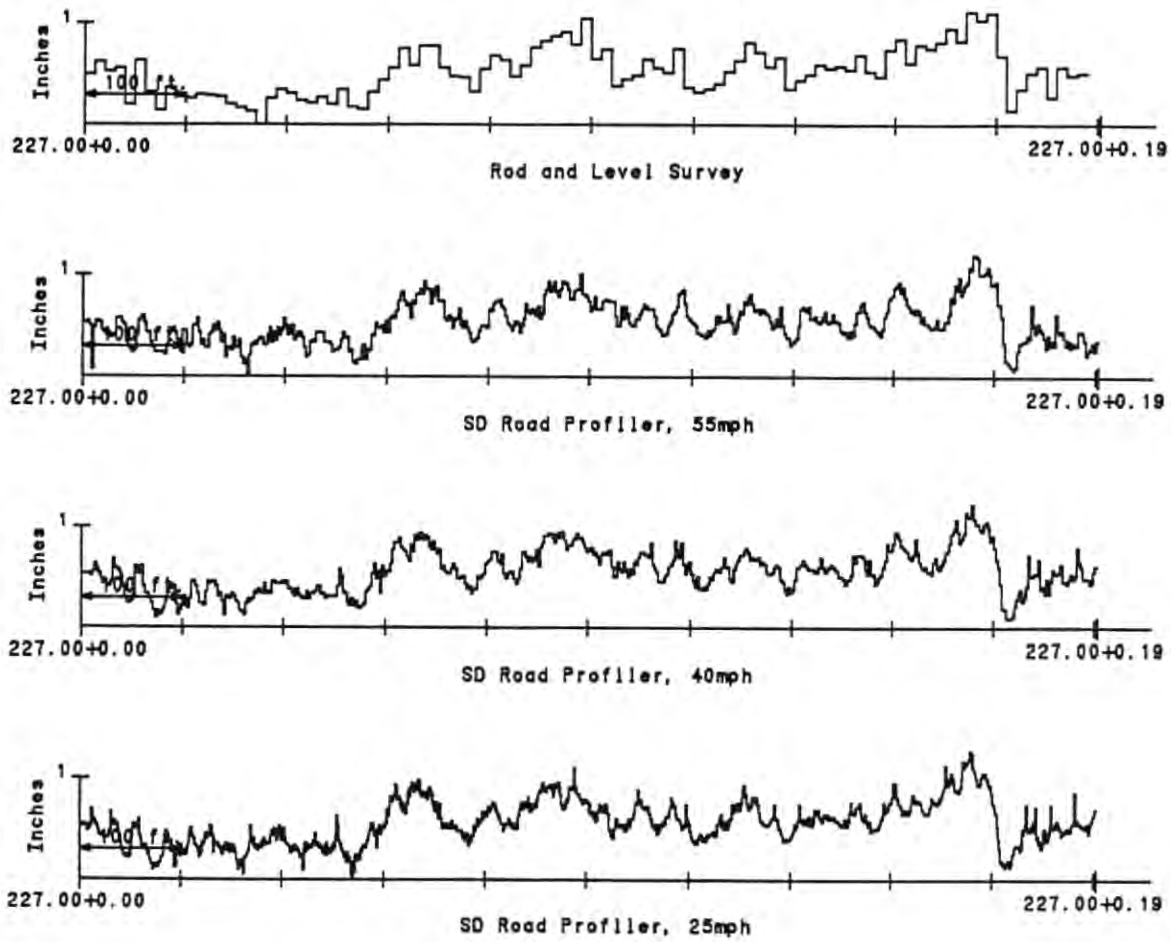


Figure 118: Site 10 Rut Depth Plots

SUMMARY AND CONCLUSIONS

CHAPTER 9

SUMMARY AND CONCLUSIONS

Since its initial development, the Road Profiler has been valuable to the South Dakota Department of Transportation. Even as it has developed, the Road Profiler has provided Present Serviceability Indexes which are consistent over time. Statewide surveys of pavement roughness have been a major component in the state's pavement management process.

The Road Profiler has provided rut depth measurements since 1986. Even though a simple, three-point rut depth estimation method is used, the measurements have been valuable for detecting problem areas, estimating rut depths and volumes, and monitoring the deterioration rates of rutting pavements. Rut depth measurements are accurate and repeatable.

South Dakota also uses the Road Profiler to record visual condition ratings. The system is a convenient means of recording any rating item which can be observed while driving at normal traffic speeds.

All of the information recorded by the Road Profiler is immediately referenced to the state highway system. When measurements are transferred to a database resident on the agency's mainframe computer, there are extremely few discrepancies between the data and the database.

The Road Profiler is economical to acquire and operate. High production rates are normal. The equipment is simple to operate, requiring little operator training. Its maintenance requirements are reasonable.

Because of its economical design, the Road Profiler has some limitations. The ultrasonic ranging devices used to measure profile and rut depth are inherently less accurate than lasers and other optical devices, so profiles contain some random variation. The ultrasonic devices also have a limited measurement rate, so measurement intervals shorter than one foot are impossible at freeway speeds. If a highway contains very short profile features, the Road Profiler may inadequately sample the profile.

Based upon the performance evaluation described in this report, it appears that the Road Profiler can overestimate the International Roughness Index by as much as 0.2 mm/m, especially if the highway has coarse texture. The Present Serviceability Index used by the South Dakota Department of Transportation, which is not as sensitive to short wavelengths, does not vary significantly with texture. Efforts will continue to evaluate the significance of these errors and determine whether they can be minimized by refinements to the ultrasonic transducers and/or the profile analysis software.

Ultrasonic transducers' accuracy limitations do not seem to adversely affect rut depth measurements. Based upon this performance evaluation, rut depths measured by the Road Profiler are within a few hundredths of an inch of those measured manually. Measurements are consistent and repeatable, provided the driver maintains a uniform course in the wheeltracks.

The South Dakota Department of Transportation has assisted several states' duplication of the Road Profiler by providing schematic diagrams, parts lists, software, and technical assistance. The Department intends to continue this policy, and hopes to form a users' group in the fall of 1989. It is hoped that technical improvements will result from cooperation, so states will have access to an economical but useful instrument.