A Road Profile Data-Gathering and Analysis System

ROGER S. WALKER and W. RONALD HUDSON, Center for Highway Research, University of Texas at Austin

A profile data-gathering and analysis system developed for the Texas Highway Department is described. This paper presents details of the overall system and demonstrates that rapid and effective data processing is essential for a usable system. The analog-to-digital data conversion and processing subsystem used in conjunction with a surface dynamics profilometer is described. The operating procedure used for gathering and validating data is presented covering both the profilometer and analog-to-digital subsystems. The analysis of the overall system includes an experiment conducted to check the authenticity of the calibration signals and detect errors in the digitization process. Many of the problems encountered during development of the overall system and corrections required to keep the system operational are described. Suggestions for needed modifications, including a noncontact sensing wheel, are discussed.

•THIS PAPER describes a road profile data-gathering and analysis system that provides quantitative records of a road profile at speeds up to 60 mph and thus can be used without causing undue traffic interference. The two major components of the road profile data system (Fig. 1) are a surface dynamics (SD) profilometer and an analog-to-digital (A-D) data conversion and processing subsystem, which is essential for effective use of the gathered data.

The SD profilometer was developed by General Motors Corporation for gathering analog profile data to use in vehicle ride simulation. However, there was widespread interest in it, and K. J. Law Engineers, Inc., was licensed to manufacture it. The SD profilometer used in this road profile system was the first one delivered by Law.

The other major component of the system is the A-D subsystem, two versions of which are available: an SDS 930 general-purpose computer with an A-D peripheral unit owned by the University of Texas, and a Hewlett-Packard 2115 computer, purchased for use with the system. The HP 2115 system is just becoming operational and is not described here. It does, however, maintain complete compatibility with the SDS equipment.

The profile data recorded in analog form by the SD profilometer could be processed in several ways, including analog and digital, but digital processing was chosen for this system to give increased flexibility and because a digital computer was available. Analog processing is satisfactory if only processing techniques such as harmonic analyses and power spectral density are to be used, but digital processing has advantages if other techniques such as variance of slope or roughness indexes, which are more difficult to obtain in analog form but lend themselves to digital processing, are to be used.

Development of the overall system brought out a variety of problems, many of them concerned with the profilometer. They are discussed here together with modifications required to keep the system operational and suggestions for permanent solutions.

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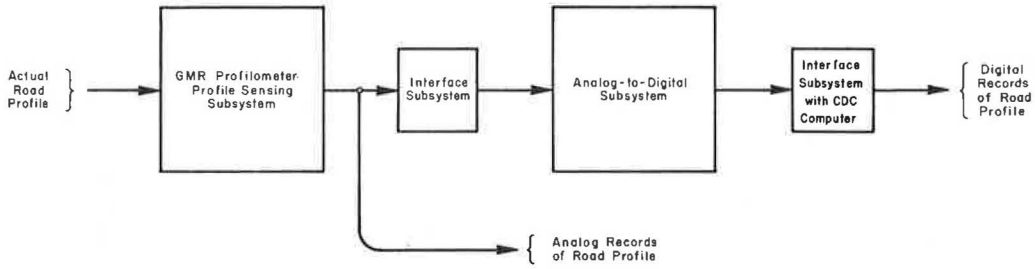

Figure 1. Profile-measuring system.

SYSTEM DESCRIPTION

The objective in developing a high-speed profile data-gathering and analysis system was to provide a capability of measuring highway profiles at highway speeds and using the resulting data in such ways as (a) evaluating the serviceability index of new or existing pavements; (b) establishing pavement maintenance priorities; (c) conducting research, such as determining whether continuously reinforced concrete pavements provide better serviceability than jointed pavements; and (d) possibly establishing roughness levels for acceptance of new construction.

A standard procedure for use in gathering and analyzing road profile data was developed. Figure 2 shows the measurement process. To determine the profile for a particular pavement, the SD profilometer is driven to the section to be measured, the proper filter and speed combinations are determined, and the electronic equipment is calibrated. The profilometer then is driven over the pavement section and the road profile measurement is recorded in continuous form by a strip chart recorder, which provides a permanent visual record of the profile, or on an analog magnetic tape recorder, or both. To obtain a digital record of this profile, the analog tape is sent to a laboratory, where the A-D subsystem computer converts the road profile measurements to discrete digital values at desired equidistant intervals for processing. Computer programs are then used to summarize the data in the form required for profile analysis. A detailed block design for the road profile data-gathering and analysis system is shown in Figure 3.

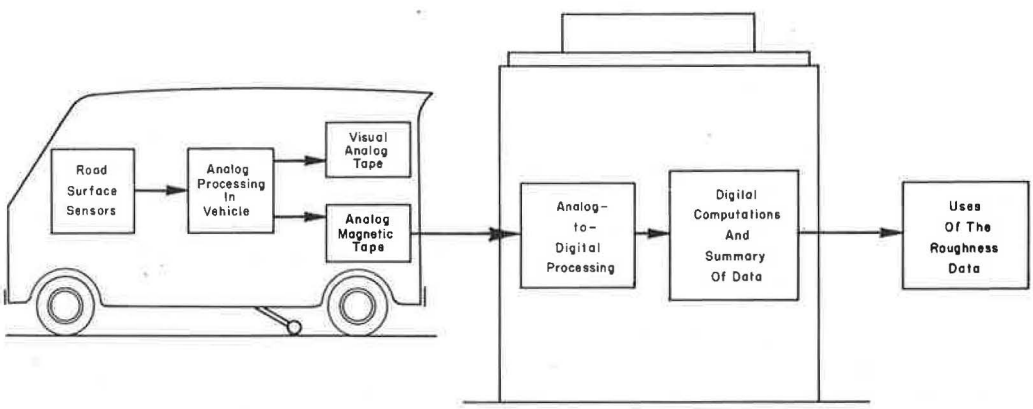

Figure 2. Measurement process.

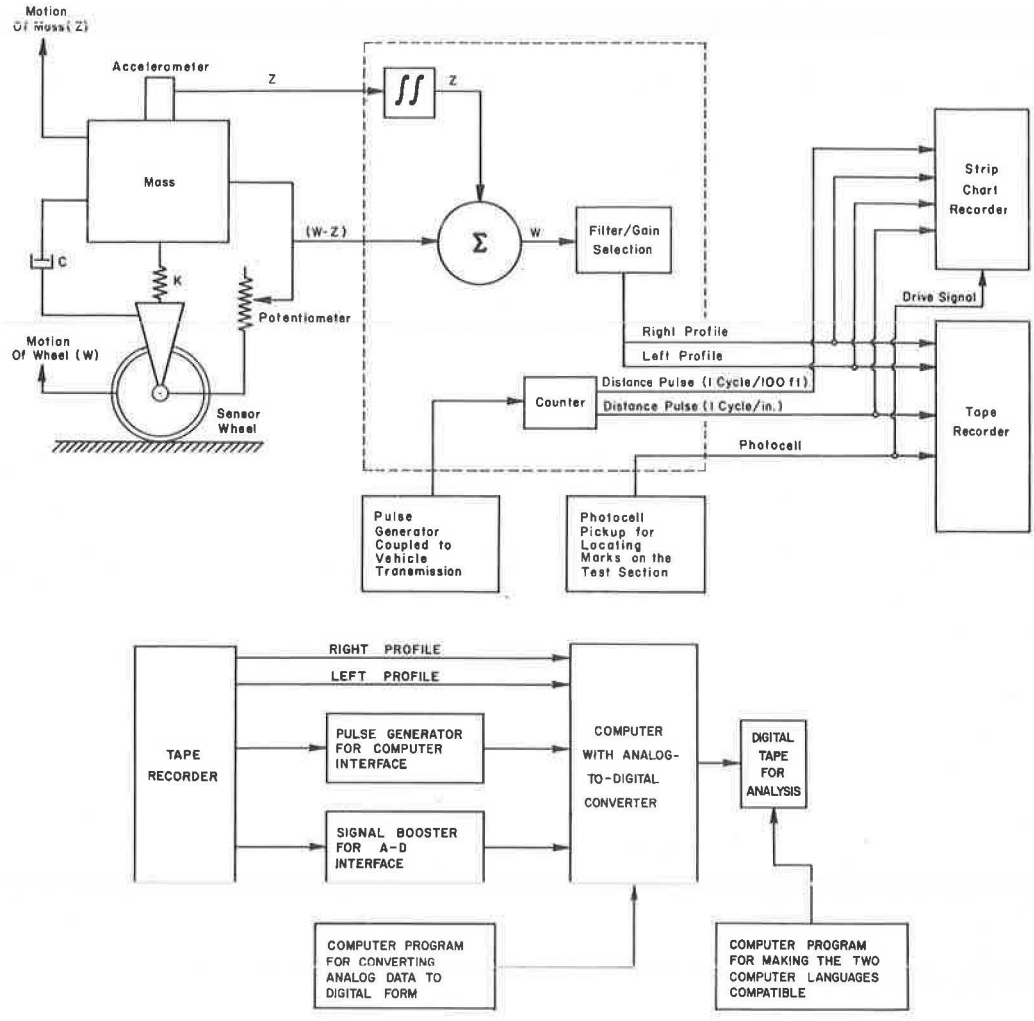

Figure 3. Detailed block diagram of measurement system.

Measuring Technique and Equipment

The SD profilometer contains all the necessary sensors and equipment to obtain an analog signal directly proportional to a roadway profile: two road-following wheels (each mounted to the vehicle and held firmly in contact with the road by a 300-lb spring force exerted by a torsion bar and a linear potentiometer), an accelerometer, and a small analog (profile) computer to sense and record data. A linear potentiometer is mounted between a sensor wheel and the vehicle body, and the difference in sensor wheel and vehicle body displacements, W - Z, is obtained by the potentiometer. The accelerometer, mounted directly above the potentiometer, induces a voltage proportional to the vertical vehicle body acceleration, $\ddot{Z}$, and the analog computer double-integrates the vertical body acceleration to obtain the vertical body displacement, Z. A voltage directly proportional to the vertical wheel movement (the road profile) is then obtained by the analog summing of the vertical body displacement, Z, and the sensor wheel and body displacement difference, W - Z. An active high-pass filtering network is used in the integrator and summing circuitry for filtering low-frequency or long-wavelength profiles, such as those of hills. Two independent measuring subsys-

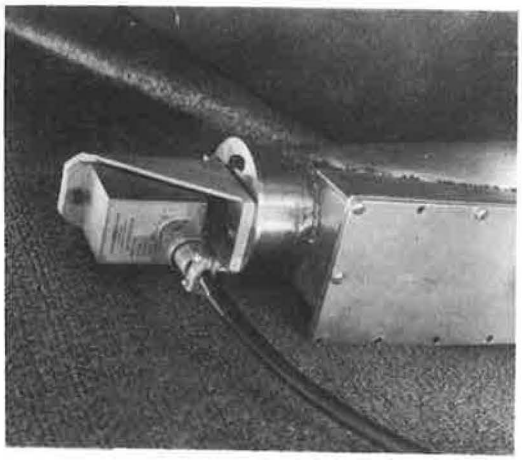

Figure 4. Systron-Donner accelerometer.

Figure 5. Road-following wheel and assembly.

tems are used for measuring profiles, one right and one left. Complete details of the measuring technique are given elsewhere (1).

The device used to measure the difference in wheel and body displacements is a Markite linear potentiometer, which its manufacturer considers to have "substantially infinite" resolution. The potentiometer output signal is scaled in the profile computer so that a 1-in. displacement of the potentiometer shaft is equivalent to 1 volt.

Vertical vehicle body acceleration is obtained with a Systron-Donner model 4310 servo-accelerometer (Fig. 4) with a ±2 g range. The output from this accelerometer is large enough so that signal amplification in the profile computer is not necessary.

A spring-loaded arm, which holds a road-following or sensor wheel in contact with the road surface, is shown in Figure 5. The figure also shows the potentiometer mounted above the sensor wheel on a wheel support and attached to the vehicle body directly above the wheel. The trailing arm can rotate about the transverse and vertical axes, but rotation about the transverse axis is constrained by the torsion bar springs. Further details of the trailing arms are given elsewhere (2).

Each sensor wheel is specially constructed, with a high strength-to-weight ratio. The natural rubber tire is molded to the wheel rim, and the outside diameter is ground to be concentric with the wheel shaft. Experience has indicated that wheel road wear is a significant factor, as is discussed later in an analysis of the system.

Road-distance measurement is obtained with a Veeder-Root rotary pulse generator coupled to the speedometer drive. The strip chart has an optional drive that can be run off a fixed-time base or by the distance pulses for a direct-distance scaling of the pavement surface.

Operation of the profilometer requires two persons—a driver and an operator—for the electronic equipment. The driver has controls for turning on warning lights, raising or lowering the trailing arms, and indicating specific events, and also has visual and audio alarm systems for indicating vehicle-speed errors and computer overloading. Pertinent data such as test section identification information and filter-gain combinations can be recorded on the voice channel of the Honeywell 8100 FM tape recorder. The vehicle has an automatic speed control system. Variations in the speed selected in the profile computer by the operator can be observed on a speed-error meter calibrated so that variations within ±5 mph of the selected speed result in full-scale meter deflections. Speed variations can also be indicated by an audio alarm provided by the profile computer. The amount of speed variation is indicated by the intensity of the signal. The intensity of the audio signal decreases as the vehicle speed approaches the selected speed and increases in proportion to an increasing difference from the selected speed.

Further information on the profilometer output signals is provided in the section on the profile computer subsystem. Two independent power systems are included in the profilometer: the standard vehicle power system and an independent supply for the profilometer equipment.

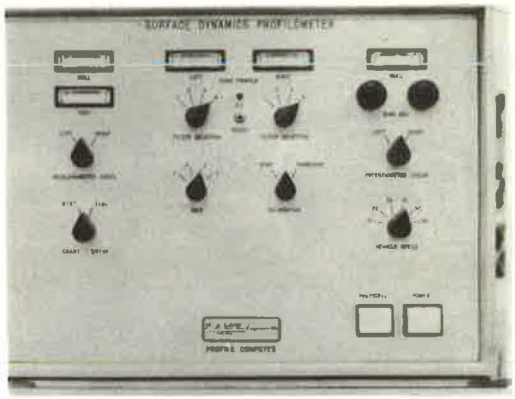

Figure 6. Profile computer.

Profile Computer

The profile computer has inputs for (a) body acceleration for right and left sides of the vehicle, (b) sensor wheel and body displacement difference for both sides of the vehicle, (c) distance traveled as denoted by pulses per foot, and (d) photocell-sensing for location of marks on the test section (Figs. 6 and 7). The computer then provides as outputs (a) the right and left road profile measurements, (b) distance traveled denoted by approximately 1 pulse per inch, (c) distance traveled denoted by 1 pulse per hundred feet, (d) a photocell-sensing signal (logical), and (e) a speed-error audio reference signal. There are three selectable parameters that affect the right and left profile measurement outputs. These are high-pass filter selection, gain or measurement sensitivity selections, and vehicle operating speed selection.

The four high-pass filter selections are used for attenuating frequencies below 0.3, 0.6, 1.0, and 3.0 radians per second. The four gains of 0.2, 0.5, 1, and 2 volts per inch are available for selecting profile gain sensitivity. As may be noted from the measuring sensors, the long-wavelength profiles affect the vehicle body and thus are sensed primarily by the accelerometer. The short wavelength profiles, such as bumps and potholes, are sensed primarily by the traveling wheel. The vehicle suspension system dampens the effects of the high-frequency, small-magnitude bumps. Because the magnitudes of the longer wavelengths vary considerably, as noted from the varied elevations of hills and dips, profile scaling, or gain selection, is necessary. By the use of the four filter selections, attenuation of the undesirable long wavelengths is possible. Because the measuring speed determines the frequency of the long-wavelength components, careful selection of a speed-filter-gain combination is required to make the best measurement of a particular section.

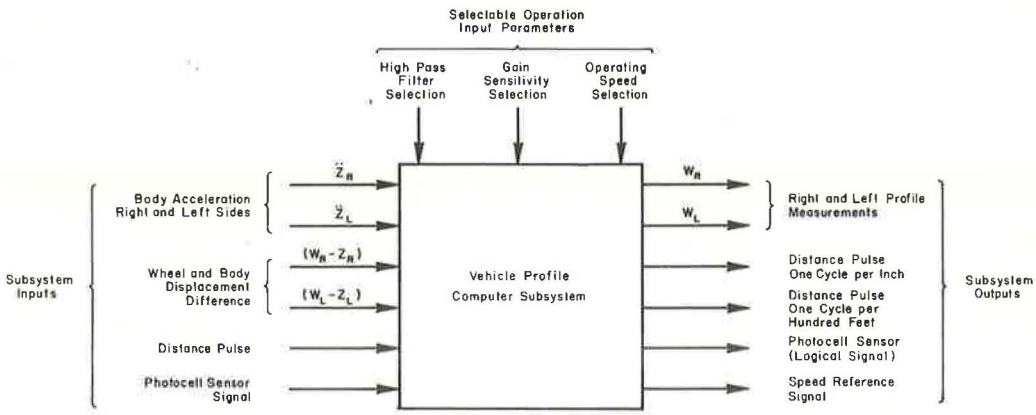

Figure 7. Profile computer subsystem.

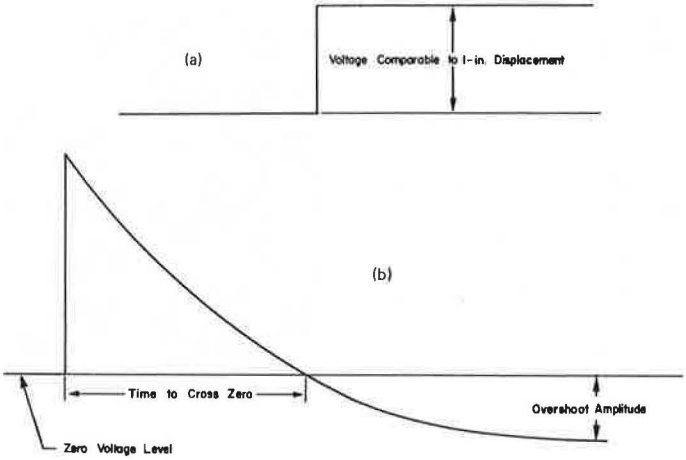

Figure 8. Typical calibration signals: (a) 1-in. displacement for scaling data; (b) transient for filter validation.

The six speed selections on the vehicle profile computer (10, 20, 34, 40, 50, and 60 mph) are used to provide a reference for the speed-error meter display so that adjustments of the vehicle cruise control can be made to reach the desired speed.

In considering the speed-filter-gain relationship from an electronic viewpoint, it should be noted that integration of dc or near-dc signals by electronic integrators results in an unbounded output as time increases without bound. Thus, the four filters help maintain stability of the profile computer by attenuating the long wavelengths. Even with these selections, however, low-frequency profile components of sufficient duration and magnitude can saturate the integrator amplifiers. To prevent this, an overload circuit was designed to short the integrating capacitors and reinitialize the subsystem. When this occurs, however, the profile signal obtained at that time and for a few seconds thereafter is erroneous.

The analog computer subsystem uses two calibration signals for scaling and filter information. The voltage amplitude comparable to a continuous 1-in. profile displacement (Fig. 8) is obtained by a simple control switch on the front panel of the computer. Similarly, the free response of the system can be obtained by a transient switch, which when activated excites the system with a voltage pulse comparable to a 1-in. impulse displacement. The high-pass filter selection can then be checked by noting the zero crossover point. When recording a 1-in. step or transient, the vehicle is normally stationary, and thus the distance pulse is zero. To provide a sampling signal for the A-D process and also a drive signal for the strip chart recorder, a constant 500 Hz signal replaces the distance pulse via a time-distance switch on the profile computer.

Recording Equipment

The strip chart recorder, a Brush Mark 280, provides an immediate permanent visual copy of the road profile. It is a two-channel analog recorder with two event pens and pressure ink-writing system providing 0.5-millivolt per chart division maximum sensitivity capability. The analog channels display the right and left road profile measurements. The 100-ft distance pulses and the photocell-sensing signal are displayed on the two event channels. Pulses from the Veeder-Root rotary pulse generator trigger the paper drive in the distance mode of operation.

The Honeywell 8100 magnetic tape recorder records information for subsequent analog or A-D processing. It is equipped with eight FM record/reproduce channels and four recording speeds. An FM compensation channel for playback compensation is

provided, as is a voice monitor channel. Four of the eight channels record right and left profile measurements, 1-in. distant pulses, and the photocell-sensing signal. A fifth channel is used to record the system ground. The remaining channels are available for any additional requirements. The voice channel is used for section identification, for speed-filter-gain selection, and for calibration information. The 42-dB signal-to-noise ratio of the FM tape system allows 8-bit resolution of digitized data reproduced from the analog tape.

Figure 9. SDS 930 computer console and equipment hookup for A-D processing.

Analog-to-Digital Subsystem

The A-D subsystem is used to digitize the analog profile signals, which are gathered by the profilometer, for digital computer analysis. The process is accomplished with an SDS 930 general-purpose computing facility. The A-D process involves the Honeywell 8100 analog tape recorder for data playback, an HP 214A pulse generator, a photocell signal-booster unit, an SDS 930 computer facility (Fig. 9) with an A-D peripheral unit, and an A-D program. The right and left profile signals are digitized into 12-bit (11 bits plus sign) data words in accordance with the distance or sampling signal. The HP 214A pulse generator is used to interface the sampling signal with the SDS 930 computer. The photocell signal-booster unit interfaces the photocell signal with the SDS facility. The digitized 12-bit data words are then written on standard digital tape in 1,500-word blocks at 556 bits per inch.

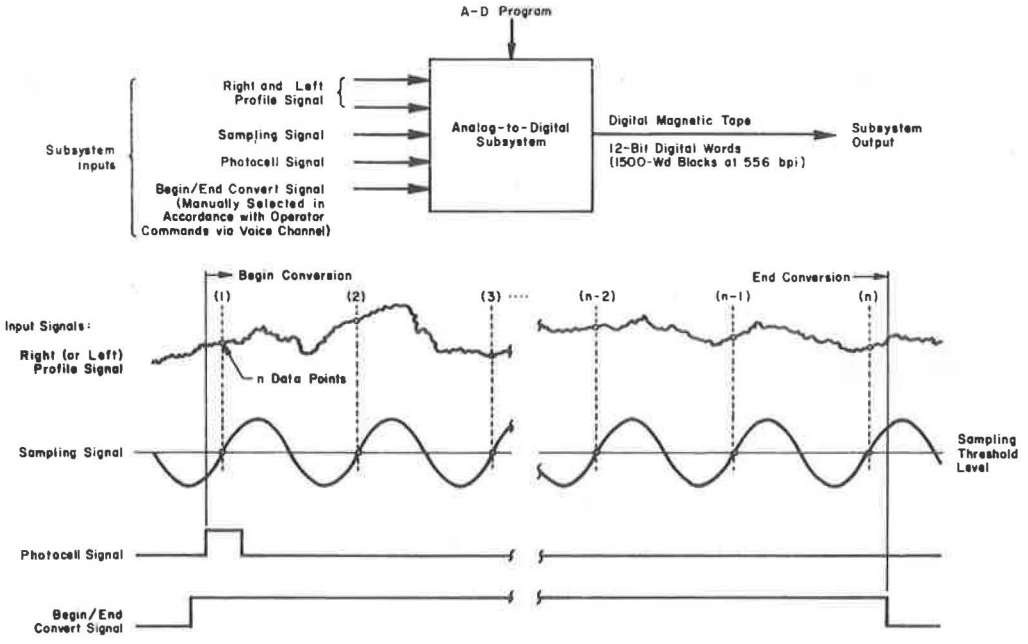

Figure 10. Analog-to-digital subsystem with inputs.

Analog-to-Digital Process

There are four primary signal inputs to the A-D subsystem (Fig. 10). Either the photocell-sensing signal and the begin/end conversion signal or the begin/end conversion signal is necessary to begin the A-D process. The begin/end conversion signal comes on first, initializing the system, and the program waits for the photocell signal to be sensed, indicating the beginning of the section to be measured and thus the beginning of the conversion process. If the photocell signal is not used, A-D operations are controlled by the begin/end conversion signal. The conversion process continues in accordance with the sampling signal until the begin/end conversion signal drops, indicating the end of the conversion process and thus the end of the digitized data file. The begin/end conversion signal is initiated and terminated manually on command from the profilometer operator via the voice channels on the Honeywell recorder.

As the analog data are digitized, they are stored in 1,500-word blocks, after which they are written on digital magnetic tape at 556 bits per inch. Thus, two memory buffers are used by the computer, one for inputting the digitized values and the other for outputting the data on the digital tape. On receipt of the end of conversion signal, a five-word identification record followed by an end-of-file is written to signify the end of the conversion process and thus the data file.

The SDS A-D subsystem has the following characteristics:

1. Sample resolution of 11 bits plus a sign bit.
2. Up to eight channels at sampling rates up to 16/N kHz per channel, where N is the number of channels.
3. Sampling rate externally driven at any external rate or reduced multiple of this rate; i.e., sampling rate equals external rate divided by W, where W is any positive integer from 1 to 2,048. For example, with a 2 kHz external sampling signal and W = 4, the sampling rate will be 2 kHz/4 or 500 Hz.
4. Sample rate internally controlled by the HP 214A pulse generator.
5. Conversion process controlled by the photocell signal and the begin/end conversion signal or simply the begin/end conversion signal.

Analog-to-Digital Program

Both FORTRAN and symbolic languages are used in the A-D program, for which the general flow chart is shown in Figure 11. Briefly, the general flow of the program is as follows:

1. The program is loaded and the operator enters various operation parameters, such as (a) whether a new or old data tape is used (e.g., if the tape is not a new data tape, the last data file or any other desired file is located and the tape is positioned to begin after that file), (b) whether the control mode is automatic or manual (e.g., if a conversion process is desired for beginning and ending the conversion process by a series of control signals and thus, without entering any new file identification information, the automatic control mode is selected), and (c) whether or not the photocell signal is to be ignored (i.e., whether or not the conversion process will be initiated and terminated solely by the begin/end conversion signal).
2. The program waits for the begin conversion and/or photocell signal command for initiating the A-D process.
3. The program uses two 1,500-word buffer areas so that one buffer is being filled by the A-D input operations while the other is emptying on the magnetic tape.
4. A new read command is immediately initiated after 1,500 words have been read to ensure that the required sampling rate is maintained.
5. The 1,500 12-bit words in buffer 1 are written in binary on the magnetic tape.
6. The procedure is repeated (i.e., the filling and emptying of alternate buffers from the A-D unit to the magnetic tape continues until the end of the analog record or section being measured is detected).
7. The conversion process is terminated by the sensing of the begin/end conversion signal when the analog record has been completed, and a five-word identification rec-

ord is written at the end of the last data record. If the next analog record is to be read soon after the end of the last record and no additional identification information is desired (i.e., if the automatic control mode was specified), the program automatically increments the data file number and waits for the next begin conversion command(s). If not, or if other identification is required, the program stops and waits for further information or commands from the operator.

8. Each data set (data records plus identification record) is separated by an end-of-file. Two end-of-files are written at the end of the last data set on the magnetic tape.

Each data set or file has an identification record generated during the A-D process that includes (a) a data file number used by the program for identification and positioning of the data tape when adding, replacing, or deleting additional data files; (b) the number of converted 1,500-word records in the data file; (c) the number of converted data words in the last record; (d) the total number of conversions in the data file; and (e) a 24-bit identification tag for additional operational information, such as filter-speed-gain selection and date.

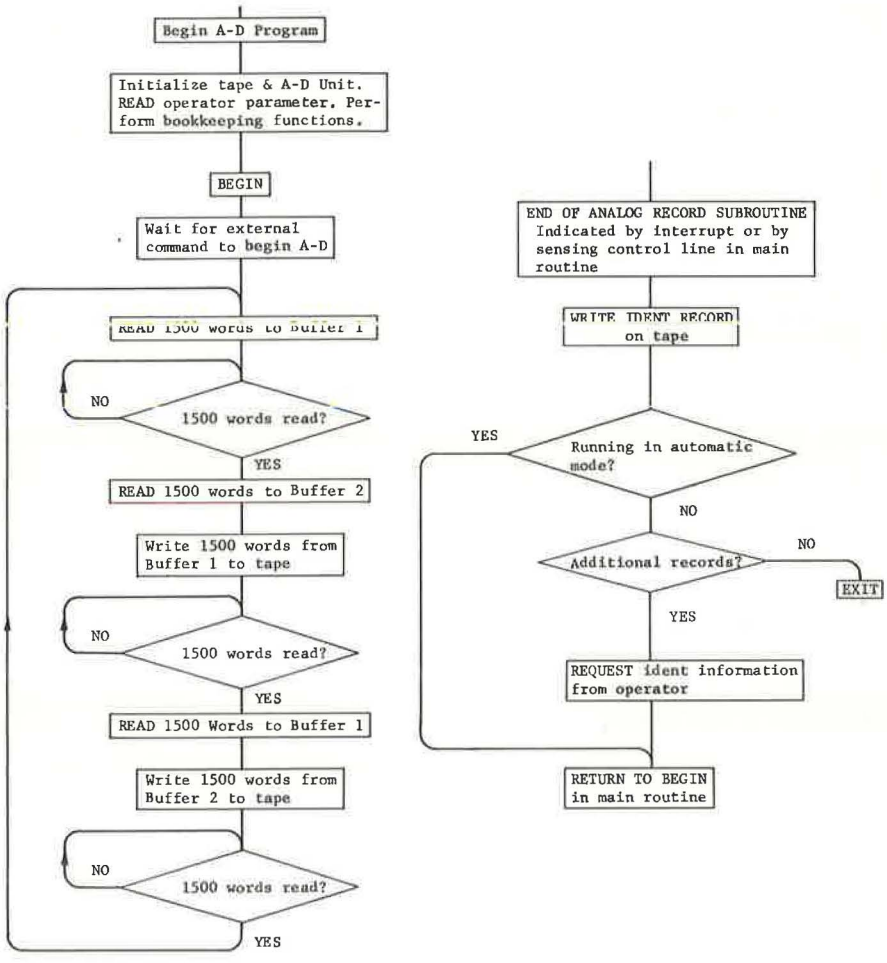

Figure 11. Analog-to-digital program for SDS computer.

Control Data Corporation 6600

After the profile data have been digitized and written on a digital tape by the SDS computer, they must undergo a transformation to make them compatible with the computer performing the data analysis. Current data analysis at the University of Texas at Austin is performed on a Control Data Corporation 6600, and therefore the SDS profile data are made compatible with the CDC 6600 data analysis programs. The changes can be made on either the SDS 930 or the CDC 6600. The compatibility program currently used is run on the CDC 6600. The program performs the following steps to transform the SDS binary data words into CDC 6600 binary data:

1. The program examines the data for possible parity errors. A continuous conversion process from beginning to end of a road section is required because of the analog tape recording. Consequently, time is not available during the digitizing process to check for bad digital tape writes. Thus, parity errors are possible when the digital tape is read. The effects of these errors may vary in statistical analysis of large samples of data, particularly if errors are omitted or replaced by approximations, and thus the importance of identifying the locations and numbers of these errors is realized.
2. The program reverses the order of each set of five 12-bit words, from one to five to five to one. This change is necessary because of the characteristics of the CDC data channel and the SDS binary write operations.
3. The program changes the 12-bit SDS binary words into 60-bit CDC binary words.
4. The program changes each binary word from the two's complement mode as used in the SDS machine to a one's complement mode as used by the CDC machine.

FILTER-SPEED-GAIN SELECTION CRITERIA

The filter and speed selection used in measurement of a road profile effectively fixes the profile wavelengths that will be measured. The response curves (4) denote the gamut of frequencies in which the system introduces no attenuation or phase shifts. Speed and wavelength are related to these frequencies by

$$\lambda = \frac{V}{f} \tag{1}$$

where

λ = wavelength, in ft;
V = velocity, in ft/sec; and
f = frequency, in Hz.

To determine a speed-filter combination for measurement of a road profile, it is necessary to determine which profile wavelength measurements are wanted. Then the proper filter-speed combination for phase shifts of 10 and 135 deg (0.7 or 3 dB attenuation) is obtained from a graph (Fig. 12). If only those wavelengths smaller than 10 ft with no phase shifts exceeding 10 deg are of interest, filter-speed selections of filter 3 at 10 mph or filter 4 for the remaining speeds of 20 to 60 mph can be used. Similarly, beginning with a given speed or filter, the necessary combinations, in accordance with Eq. 1 and the system frequency constraints of Walker, Roberts, and Hudson (4), can be found.

Four gain selections are provided by the profile computer for profile data scaling. The computer is designed for a voltage operation of ±10 volts. Voltage amplitudes exceeding this range overload the computer and cause erroneous data. For a given data run, maximum resolution is obtained when the profile voltage amplitudes are as large as possible, but it is necessary to take care not to exceed the ±10-volt range of the computer to avoid jeopardizing the entire data run. The ±10-volt critical magnitude can be violated easily if the full-scale reading is too close to this ±10-volt critical magnitude, because the accelerometer and thus the voltage output changes are quite sensitive to speed variations.

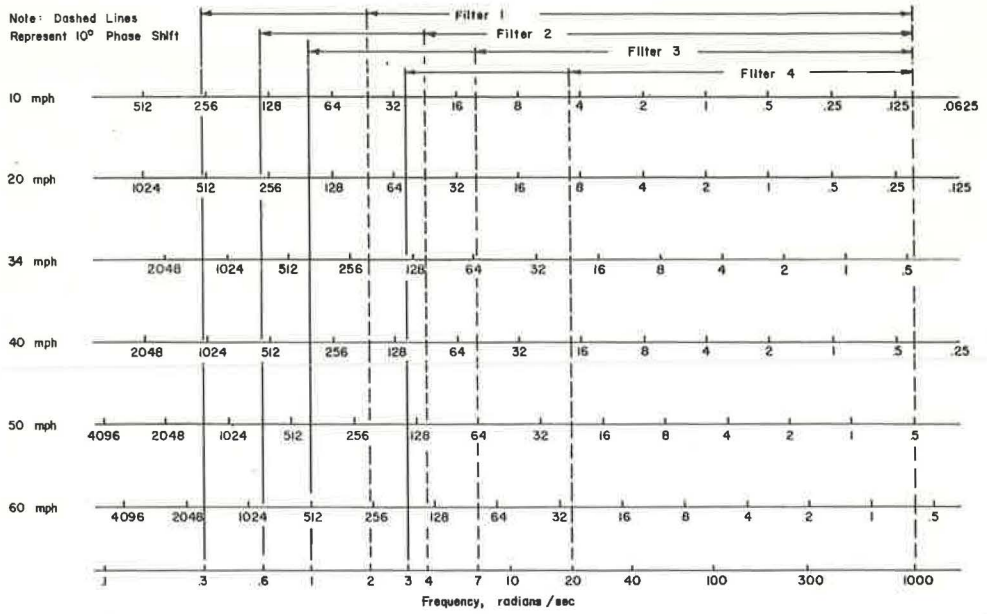

Figure 12. Filter-speed wavelength selection graph.

ANALYSIS OF THE SYSTEM

Various system analysis techniques were used to determine the authenticity of the data obtained by the profile-measuring system. A system analysis procedure was used to ensure the validity of the profile data at the various stages in the data-measuring flow path. It was instrumental in development of the total measuring system and is currently used for isolating equipment problems or failures. The digitizing process was examined closely to determine if significant errors that could lead to misleading or erroneous road profile measurements were introduced. An experiment conducted to establish the significance of any such errors is described in the following section. To examine the sensitivity of the measuring subsystem to typical environmental conditions such as weather and operating techniques, an experiment was conducted to determine the sensitivity of the major electronic components of the profile computer to typical changes in the operating environment. The sensor wheels were analyzed also to determine a solution to the problem of rapid wear. The frequency response of the system was also checked and is documented elsewhere (4).

System Analysis Procedure

Because of the size and complexity of the profile-measuring system, a systematic procedure was developed for use in the early detection of system failures and to aid in the initial system development (Fig. 13). Basically, this analysis procedure identifies the most likely failure areas and the facilities available for rapid detection of the failure. A typical example of the need for such a procedure is the early detection of a noisy channel in the analog recording unit that could lead to misleading results when the road profile data are being analyzed. To develop the test procedure, checkpoints along the data flow path were selected where subsystem failure could affect the measurement process; thus, each checkpoint could be used to verify the system operation to that point. The entire test procedure should be followed as standard operating practice to ensure satisfactory system operation and, if a failure occurs, as a guide for isolating the problem cause.

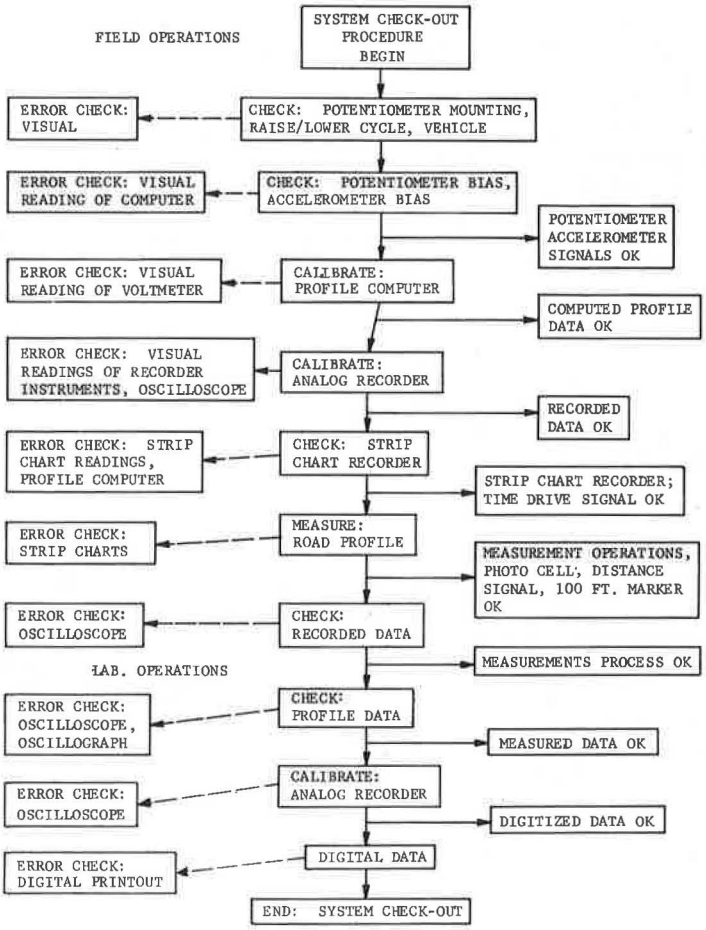

Figure 13. Schematic of system analysis procedure.

The procedure is as follows:

1. Examine the potentiometer mounts and wheel assembly for possible breakage. Check the raise/lower cycle to ensure that the wheels raise, lower, and latch properly. An inoperative road-following wheel will give erroneous profile data or introduce considerable noise.

2. Test the potentiometer and accelerometer for proper bias and operation with the test switches on the profile computer. A failure in either potentiometer or accelerometer can result in erroneous data, frequent computer overloads, or considerable noise in the data.

3. Verify operation of the profile computer by balancing the operational amplifiers. Test the filters by observing the transients on either the oscilloscope or the strip-chart recorder. Erroneous profile data or noise can be introduced by a malfunctioning profile computer.

4. Calibrate the Honeywell 8100 analog tape recorder to ensure proper recording. An inoperative recorder can result in the complete omission of a channel or can introduce noise in the data.

5. Calibrate the strip-chart recorder; once it is set up properly, it can be used for continuously checking the operation of the measuring process.

6. Validate the operation of the photocell, the time-distance pulse, the 100-ft event maker, and the right and left profile data by making a test run of the vehicle with the strip-chart recorder in use.

7. Periodically play back the Honeywell recorder via both the strip-chart recorder and the oscilloscope to ensure proper recording. The oscilloscope check ensures that noise was not introduced into the data.

8. Check the profile data, photocell signal, and timing or sampling signal brought back to the laboratory for A-D processing by using the oscilloscope and the light-beam oscillograph. The light-beam oscillograph (wide-band response) provides a high-frequency hard-copy output for comparison with the strip-chart (limited bandwidth) records.

9. Calibrate the Honeywell 8100 analog tape recorder to ensure proper playback operation for the A-D process. An inoperative recorder can result in the playback of data with considerable noise or no signal at all.

10. Make periodic checks of the digitized data to confirm the validity of the digitizing process. Malfunctions in this process can add noise, provide erroneous data, or intermittently fail to sample the data signals.

Redigitization

An experiment was conducted in which a known signal was recorded and then redigitized several times to ensure that system accuracy, as determined by the least accurate subsystem, the Honeywell 8100 tape recorder, was maintained in the digitizing process. The results indicated that the accuracy of the digitizing process was within the accuracies of the Honeywell 8100 recorder, i.e., 8 bits ± least significant bit.

In the experiment, a 1,000-Hz signal was recorded on two channels of the Honeywell 8100 magnetic tape recorder. The 1,000-Hz frequency is considered to be the upper limit of the sampling frequencies for typical data runs. The upper limit was selected because of the nature of the digitizing techniques—i.e., the greater the sampling frequency, the less the expected system resolution capability. The two channels were then played back into the SDS 930 computer facility, one channel into the analog input for sampling and the other into the external interrupt input to initiate the sampling process (Fig. 14).

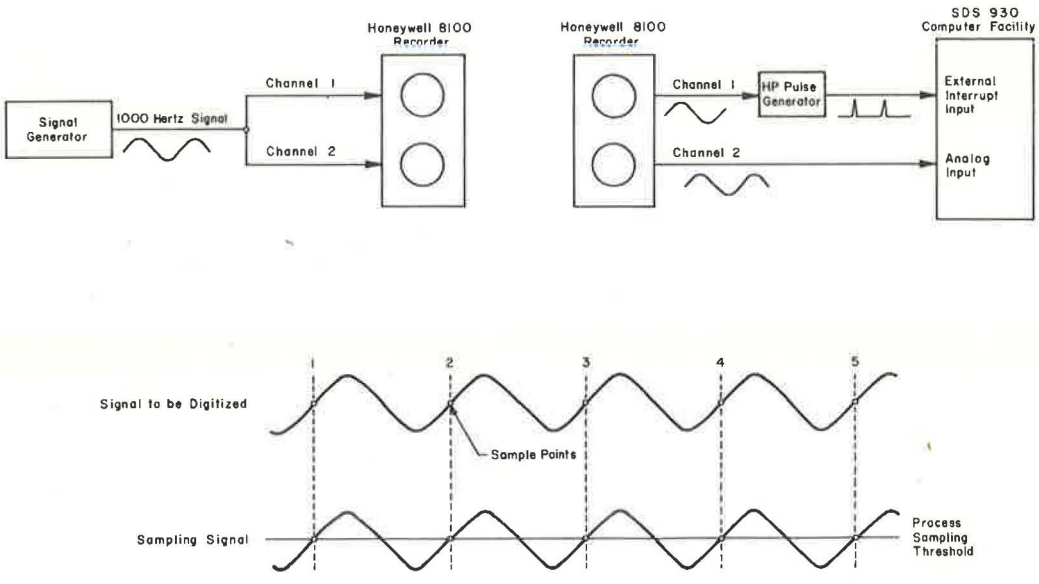

Figure 14. Sampling configuration.

As noted before, the computer samples the analog input channels in accordance with the sampling signal; i.e., each cycle of the sampling signal is used to interrupt the computer, which in turn initiates a conversion process to read and store the 12-bit digitized value. By using the same signal for both the signal to be digitized and the sampling signal, a consistent set of digitized results can be obtained. This signal was digitized five times, beginning at the same point each time, to check the repeatability of the digitizing process. The 8-bit results were converted from the 12-bit values by adding 8 to each 12-bit word and then dividing by 16. The largest variation between successive redigitizing was of the magnitude of one, which is the best accuracy that can be expected from the recording device, i.e., 8 bits ± least significant bit. Thus, it was assumed that the digitizing process was within the system accuracies as established by the Honeywell 8100 recorder, and redigitization of subsequent data runs confirmed these results.

It should be emphasized that the accuracy of interest is of the entire digitizing process—i.e., using a recorded sampling signal to signal the computer to initiate the conversion process—and not in a single digitization, because the SDS converter is accurate to within 12 bits ± the least significant bit. The A-D converter is checked periodically by standard SDS diagnostic programs.

Scale Factor Sensitivity

To scale the profile data from volts to inches, the profile computer can provide a calibration voltage proportional to a 1-in. change in road profile. This 1-in. voltage signal, recorded prior to each profile measurement run, is digitized along with the respective profile data for a particular section. The magnitude of the digitized 1-in. step is the difference between the average of the points before the voltage step and the average of the points after the voltage step, as shown in Figure 15. Once this magnitude has been determined, the digitized road profile points are divided by this scale factor value to obtain a set of scaled road profile deflections in inches. It was noted that, when the 1-in. steps were recorded, there were variations in the magnitudes of these steps between right and left profiles for different filter-gain combinations, as well as between the same channels with the same combinations for subsequent readings. The concern for such variations is easily understood if it is realized that (a) these same variations could probably be expected in the profile signal itself, because many of the

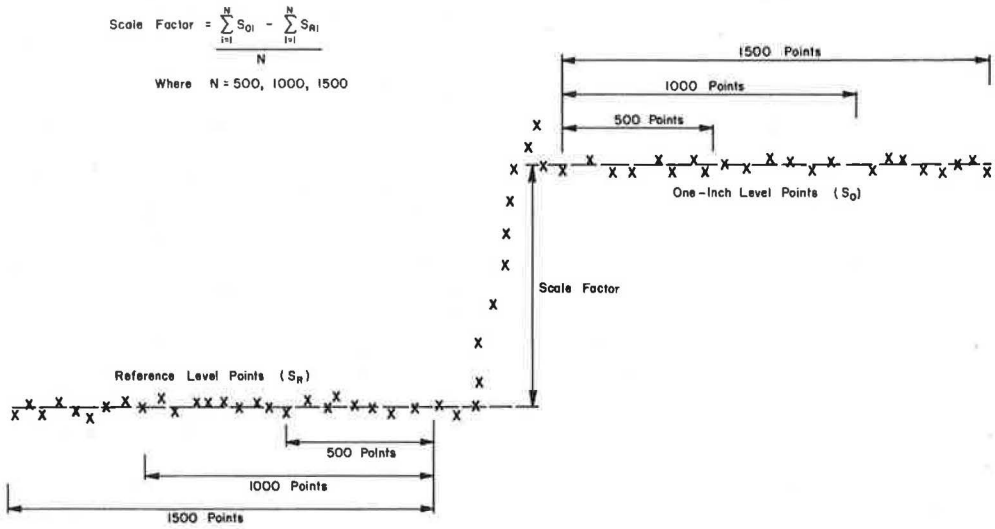

Figure 15. Schematic of scale factor computation.

				Profile Signal							
				Right Profile				Left Profile			
				Filter				Filter			
				1	2	3	4	1	2	3	4
Gain	1	Technique	3								
			2								
			1								
	2	Technique	3								
			2								
			1								

(4 Observations per cell)

Figure 16. Scale factor experiment design.

electronic components are shared by the calibration circuitry and the profile-measuring circuitry, and (b) all the profile measurements are scaled by these 1-in. calibration steps.

To determine the significance of these variations on the measuring system, an experiment was conducted in which several 1-in. steps for the various filter-gain combinations were randomly obtained (Fig. 16). Because electronic components are typically heat-sensitive, the experiment was conducted during the middle of an unusually warm day, when the variations should be at a maximum. The 1-in. calibrations were obtained and recorded in a fashion similar to that used during a typical profile-measuring operation. An accurate 1-volt signal obtained from a dc power supply as a base for computing the difference in gain selections was recorded with these calibration signals. The 1-in. steps were digitized and their respective scale factors were determined. Three averaging techniques (500-, 1,000-, and 1,500-point averaging) were used to determine if the number of points used had any effect in the scale factor computing technique (Fig. 15). Table 1 gives the analysis of variance used for obtaining the previously mentioned results. The analysis of variance was run on the difference between the scale factor obtained from the digitized measured calibration voltage and the actual value.

From this experiment, it was concluded that (a) the variation was well within the measuring accuracy of the system and it made no difference which filter-gain

TABLE 1

ANALYSIS OF VARIANCE SCALE FACTOR EXPERIMENT

Source	dF	SS	MS
Filter (F)	3	195.97	65.32
Gain (G)*	1	487.05	487.05
F × G*	3	1,715.58	571.86
Side (S)	1	213.36	213.36
S × F	3	258.00	86.00
S × G	1	140.77	140.77
S × F × G	3	516.98	172.32
Error (a) Replication (R), R × F, R × G, R × F × G, R × S, R × S × F, R × S × G, R × S × F × G	45	2,723.69	60.70
Technique (T)	2	0.71	0.36
T × F	6	9.26	1.54
T × G	2	8.29	4.14
T × F × G	6	45.93	7.65
T × S	2	3.54	1.77
T × S × F	6	4.78	0.80
T × S × G	2	2.70	1.35
T × S × F × G	6	54.52	9.09
Error (b) T × R, T × R × F, T × R × G, T × R × F × G, T × R × S, T × R × S × F, T × R × S × G, T × R × S × F × G	96	268.70	2.80
Total	191		

*Significance is expected because the gain is a multiplication factor.

combination was used for the scale factor, and (b) no difference existed in the averaging technique used for computing the scale factor. Subsequent experiments revealed that 100-point averaging provided adequate scale factor results and it is currently used in determining scale factors. Obviously, the gain selection should be made in accordance with the gain used when measuring the road profile, but the filter selection need not be the same. In fact, it was found that a usually better calibration reading was obtained with the filter 4 selection. This would be expected, considering that the higher cutoff frequency of filter 4 causes a more rapid attenuation of the system to the zero equilibrium point, which is used in the scale factor computing technique as the base or reference value.

Sensor Wheel Analysis

As noted, the life of the sensor wheels has been much shorter than expected; they have had to be replaced after 400 to 500 miles of road use. Because the cost of a wheel is about $500, this wear is considered excessive, and consequently investigations are currently in progress to find a less expensive, but usable, wheel. Two substitute wheels currently being evaluated cost less than $50. From initial test runs, it appears that there are some differences between the upper frequencies of the profile made with one of the replacement wheels and those of the profile made with the original equipment wheel. Further analysis will indicate whether or not these differences are within acceptable error limits of the overall system. It is hoped that these investigations will also provide some measure of the amount of wear a wheel can be subjected to and still provide meaningful results.

Investigations are also in progress to identify the influence of wheel characteristics, such as wheel bound, on the measured data. Use of the profilometer to date has indicated the existence of some periodic wave forms in much of the data. This wave is generally more prevalent in roads with rough textures, such as those with surface treatments. Power spectral analysis and coherence on selected combinations of various surface treatments and road types and analysis of variance are some of several analysis techniques being used to identify and determine the significance of these wheel characteristics.

SYSTEM PROBLEMS

As in all newly developed systems, a number of problems had to be solved before a workable road profile data-measuring system could be developed. The majority of these problems occurred in the profilometer, but, as noted, the profilometer used was the first one manufactured. For that reason, these problems were not considered to be unreasonable, although there did appear to be an unusually large number of them associated with the vehicle engine. The problems often resulted in considerable frustration and delays. Some of the more serious problems encountered, together with the steps taken to alleviate them, are given in the following.

Potentiometer

1. Failure of the potentiometer wiper shaft connection to the wheel assembly required that the connection be redesigned for a male-type connector.
2. Inability of the sleeves on the wiper to maintain their structural integrity made it necessary for the sleeves, which were originally sweated on, to be welded on.
3. Damage to the bearings for the wiper shaft when the wheel assembly was raised, because of excessive travel in the hydraulic actuator, required that limit switches be replaced to provide positive limit adjustments.

Distance Pulse Generator

1. Intermittent loss of the distance pulse because of poor connection of some of the leads in the pulse generator made it necessary that the leads be resoldered.
2. Loss of the distance pulse signal because the temperature environment of the Veeder-Root generator exceeded the design requirements made it necessary for the Schmitt trigger circuit, which was breaking down, to be bypassed.

Photocell

1. Severing of the power leads on the photocell lamp necessitated replacing the leads.
2. Continual breakage of the photocell lamp made it necessary to develop a better mounting technique.

Automatic Speed Control

Improper operation of the speed control unit required that the motor and drive gear in the speed control unit be replaced.

Power Supply

Because the Brush equipment failed to operate on the square wave 500 va inverter, a "Power Com" sine wave inverter for the Brush equipment was installed and the Brush pulse generator repaired.

Trailing Arm Hydraulic Life

1. Failure of the trailing arms to catch properly in some situations made it necessary that limit switches, the hydraulic actuator, and the timing control switch be adjusted.
2. Because the trailing arm stabilizer spring failed frequently, an inexpensive spring was found and large quantities were purchased for replacement.
3. Frequent failure of the potentiometer shaft mount yokes on the trailing arms required that the support brackets be welded to yokes.

Tape Recorder

1. Recorder was inoperative when delivered by the manufacturer and it was sent to Honeywell for repair.
2. Failure of discriminator and record zero adjustment trim-pot made it necessary for Honeywell to replace all trim-pots.

Profile Computer

1. Failure of capacitor mounts because of vibrations made necessary the redesign of mounting brackets to withstand vibration.
2. Failure of the integrated circuit and an R-S flip-flop in counter circuit made it necessary to replace the integrated chip.

Vehicle Engine

1. Valves and rod bearings were burned out when the vehicle was delivered, and the engine had to be rebuilt.
2. Because of frequent overheating the fan was changed and a shroud was installed over the fan.
3. The timing gear had to be replaced.

SUMMARY AND CONCLUSIONS

A detailed description of a high-speed road profile data-gathering and analysis system, including general operating criteria, analog-to-digital operations, and system checkout and data validation techniques, is presented in this paper.

The profilometer, which is a major part of the overall system, provides an accurate record of low-frequency components in the road profile, but higher frequency data have been found to be somewhat distorted because of wheel bounce at operating speeds above 34 mph. The amount of distortion is a function of vehicle speed and profile roughness, and studies are continuing in order to determine the amount and significance of these distortions.

A second significant noise problem that has been found is due to tape flutter that occurs when the vehicle is driven over roads that are rough but not considered to be excessively so. Experiments are under way to find a better mounting technique to eliminate this problem.

In general, the time required for processing profile data with the A-D subsystem and profile summary routines is often lengthy, especially when immediate results are desired. It appears that there would be some advantage to providing a profile summary device, for use in conjunction with the profile computer, that would provide immediate estimates of road roughness or other such characteristics while a profile run is being made. The accuracies of such a device would, of course, have to be carefully determined.

The weakest link in the overall system appears to be the sensor or road-following wheels. Considering their high cost, the usable life of about 500 miles is too short. The wheels have been found to be too susceptible to cutting, and the frames are often damaged when measurements are made on rough portland cement concrete pavements. To remedy this problem, two substitute wheels are currently being evaluated.

Extreme care is required in general operation of the road profile data system because of the many possibilities for introducing erroneous mechanical and electrical noise into the profile. For this reason, the data for this study have been monitored after data runs with an oscilloscope and oscillograph because of the inability of the Brush recorder to respond to most high-frequency noise.

Although the profilometer has been found to be useful to the research engineer, it is a subsystem, and considerable care in planning and analysis must also be given to the overall system if accurate road profile data are to be obtained.

APPLICATION OF RESEARCH RESULTS

Because an adequate operating manual for the SD profilometer was not provided by the manufacturer, a detailed calibrating and operating manual was developed for future use (4). This paper provides some of the information described in the report and may be of use to other users of the profilometer.

The road profile data-measuring system will continue to be used to evaluate the pavement serviceability index, pavement roughness, and road profile. Specific uses in the future include the following:

1. Aid in establishing priority for major maintenance, reconstruction, and relocation. Roughness values obtained with this equipment, along with information from traffic studies, could be used to make objective rankings for various pavement sections.
2. Aid to the design engineer in determining the degree of success with which his design has met the design criteria and to help him learn the causes for failure. To successfully evaluate a design system, accurate measurements of the system output function should be made during the entire design life of the pavement. Such measurements would provide an objective indication of the performance and the success of the particular design.
3. Aid in establishing levels of roughness that are acceptable for new construction.

To make the system more useful, further studies should be conducted to determine differences between profile data and erroneous data introduced from wheel bounce and noise. Assistance in achieving this can be provided by use of analysis techniques recently developed at the Center for Highway Research that will help to establish undesirable frequency ranges. Briefly, the procedures for the analysis would involve removing various frequency ranges by the use of digital filtering techniques and noting the effects on the resulting profile data and summary statistics. Power and cross-power spectrum analysis, regression analysis, and analysis of variance are useful tools in determining the significance of these effects.

Studies to develop better techniques for data validation during the measuring process, for early detection of noise or equipment malfunction, should be continued as well. In pursuing the problem, a suitable in-vehicle summary device could be used as an indicator of erroneous profile data; it would also be of great value in providing

rapid road-profile evaluation. Although the accuracy may be less than with existing processing techniques, the device would significantly enhance the use of the SD profilometer.

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