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SYSTEM DESIGN CONCEPTS AND PROFILOMETER CORRELATION PROGRAM PLAN

INTERIM REPORT

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UMTRI The University of Michigan Transportation Research Institute

INTERIM REPORT

System Design Concepts
and
Profilometer Correlation Program Plan

Project: "Methodology for Road Roughness Profiling and Rut Depth Measurement"

Contract No. DTFH61-83-C-00123

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16. Abstract

This report presents the plans for design, construction, and verification of a road profilometer system. The design concept is derived from functional and economic analyses of the operation of a profilometer in a highway department environment.

An inertial profilometer design is proposed using noncontact sensors as road followers by which road profile and rut depth can be measured. The data acquisition system is designed around an IBM PC computer performing control and data handling tasks. A signal-conditioning system designed by UMTRI allows computer control of setup and calibration on all data channels. Mass storage of data is provided via a digital cassette recorder. The overall design is described, along with plans for validating the system. The validation involves comparison to other profilometers in a Correlation Program to be held in Ann Arbor, Michigan in September of 1984.

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1.0 INTRODUCTION

The main purpose of this project is to develop of a state-of-the-art road profilometer that represents a rational compromise between cost and capabilities, to serve as a FHWA demonstration unit by which the technology can be introduced to personnel in state highway departments and transportation agencies.

Consequently, the first two tasks in the project have evaluated:

1) The state-of-the-art equipment and computer programs available for profilometry purposes.
2) The functional and operational needs in use of a profilometer.
3) The economic considerations in the purchase and maintenance of profilometry equipment in the environment of a state highway department.
4) The need for comparative measures of performance among various profilometer concepts.

From these analyses have emerged the various concepts by which profilometers can be designed to best meet the needs and constraints existent in state highway departments. One purpose of this report is to present the design concept that best meets these needs in order to gain FHWA technical concurrence before beginning construction of a demonstration unit.

The second purpose of the report is to present a plan for a profilometer correlation program to be conducted in the project as means to assess the performance of the FHWA profilometer in comparison to various other profilometers in current use. Such information is not available at this time; yet it is essential for state highway departments and transportation agencies to make informed decisions about what profilometry equipment will best serve their individual needs.

Sections 2 and 3 of this report present the profilometry system design concepts and the plan for a profilometer correlation program. Some important technical and practical considerations relating to the profilometer system design concepts are discussed separately in appendices that may be consulted when more background or technical justification is of interest.

The topics presented in the appendices represent somewhat independent analyses of the various considerations in design of a profilometry system. Appendix A deals with the functional purposes that have been identified for profilometer systems and the operating modes in which they may be used. It is these items that establish the performance requirements for the system design concept proposed. Appendix B addresses the technical details of the hardware needed to measure road profile, and the trade-offs among various choices available. Appendix C presents the results of an analysis of the economic considerations in purchase and operation of a profilometer system. These results, in part, guided the choices in development of the system design concepts, but may also be of interest to state highway department personnel contemplating the acquisition of a profilometry system.

2.0 SYSTEM DESIGN CONCEPT

2.1 Introduction

There are many ways in which hardware can be assembled to measure the longitudinal elevation profile and rut depth of a road surface. The experience to date in the United States, as well as the technical understanding of functional performance, favor the inertial profilometer concept pioneered by the General Motors Corporation in the 1960's for measurement of the longitudinal profile. Therefore, the inertial profilometer concept is proposed here. With this method the surface elevation is measured relative to an inertial reference provided by vertically oriented accelerometers. To maximize the accelerometer accuracy, these are placed on the chassis of the moving vehicle and the road surface relative to the vehicle is detected by a "road follower" system. A functional diagram of such a system is presented in Figure 1. The measurement of rut depth is achieved by detecting elevation differences in the transverse direction from a series of road follower sensors.

The implementation of this system in actual hardware involves many other considerations. Appendices A through C provide detailed discussion of the items that should be weighed by the designer of a profilometer system. In a generalized sense the important criteria guiding the design proposed here are as

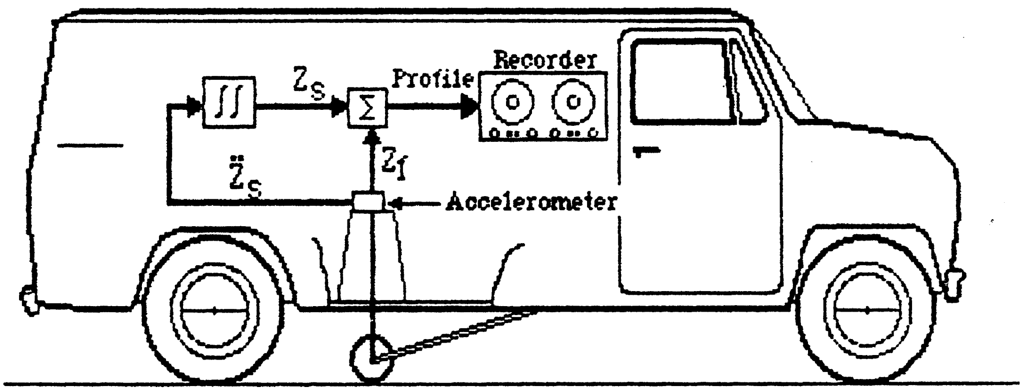


Fig. 1. Functional diagram of inertial profilometer

follows:

1) Maximum utilization of commercially available parts and components.
2) Minimum initial cost consistent with functional requirements.
3) Maximum utilization of a computer to replace specialized training and skills required of operator.

2.2 System Concept

The proposed system will consist of hardware and an operating system (commercial and specially written software) which can be installed in any convenient vehicle. The FHWA-owned van provided for the project will be the vehicle in which the system is mounted. The major components are shown schematically in Figure 2.

2.2.1 Transducers

For measurement of profile and rut depth it will be necessary to have an array of transducers by which it is possible to determine the distance from the vehicle to the road along several tracks (road followers), the vertical motions of the vehicle body (accelerometers), and the speed and travel distance of the vehicle.

Monitoring the distance from the vehicle to the road surface for the purpose of measuring the elevation profile (roughness) requires one noncontacting optical sensor for each wheeltrack measured. These will be mounted on the exterior of the vehicle

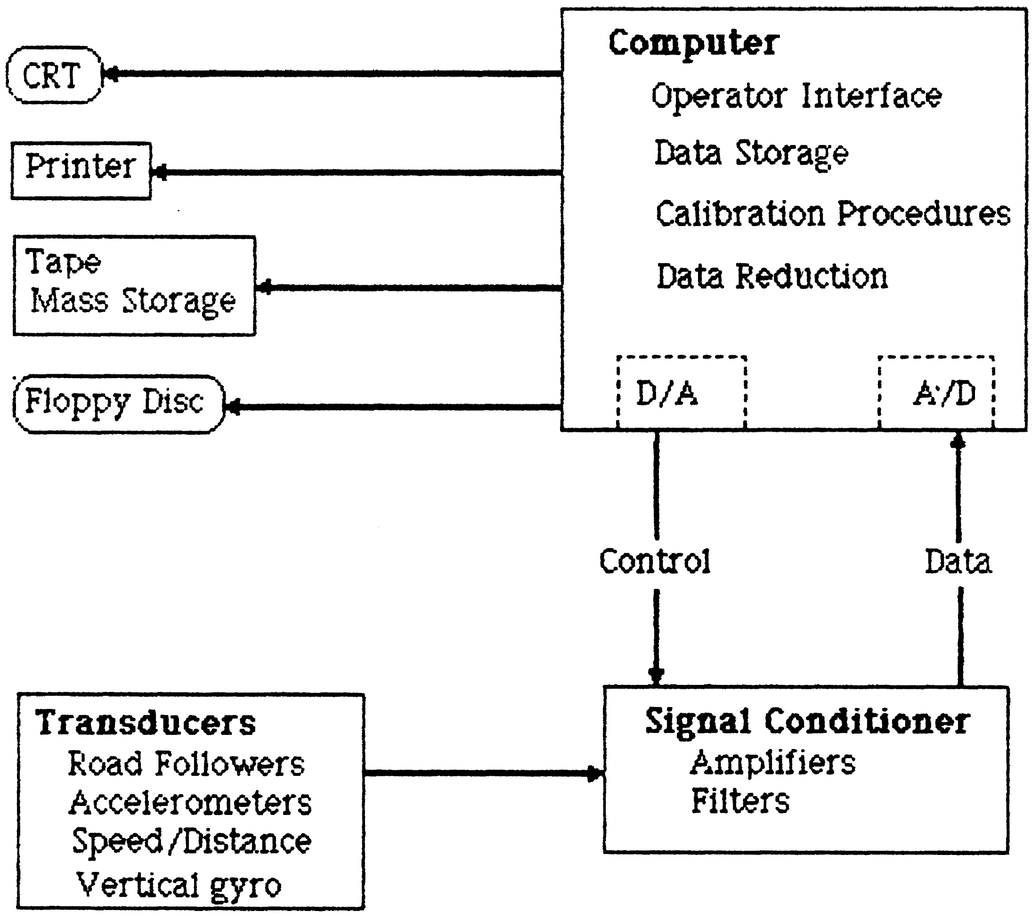
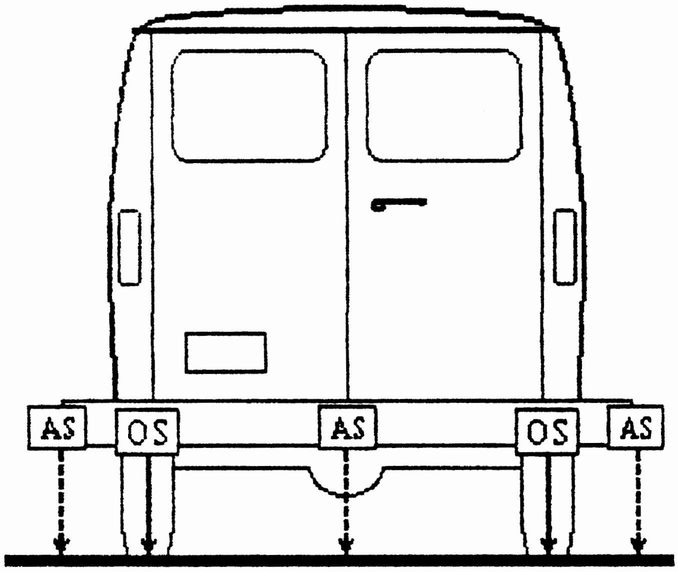


Fig. 2. Components of profilometer instrumentation system

as illustrated in Figure 3. One or two of these sensors will be required, depending on whether the system is configured for measuring one or both wheeltracks. In general, it is advisable to measure both wheeltracks because of the differential roughness that is common on many roads (the right wheeltrack often deteriorates more rapidly than the left). The profile transducers must be fairly precise devices. The distance measurement must be accurate to 0.020 inches or better to ensure accurate measurement of the roughness on the smoothest roads. Further, to ensure that the measured profile contains enough detail from which to validly predict the response of road-using vehicles, measurement capability down to 3 inch intervals is desired. For a measurement speed of 55 MPH, therefore, the profile transducers must have a bandwidth on the order of 322 Hz. The IR Noncontacting Sensors from Southwest Research will initially be used for this application, although Selcom sensors to be loaned to the project from the FAA will also be evaluated on the system.

The measurement of rut depth requires additional road-follower sensors to determine the nominal road surface height along additional tracks outside of the wheeltracks. As yet, there are no well-established procedures for measuring rut depth from a moving vehicle. In an idealized sense, the complete transverse profile would be measured in order for the high and low points to be determined across either one or both wheeltracks, such that the rut depth can be described either by the straight-edge or stringline methods. The more practical



AS - Acoustic Sensor

OS - Optical Sensor

Fig. 3. Mounting of noncontact sensors

approach, matching the scope of this project, dictates the use of one to three additional road followers located to the outside or between wheeltracks as illustrated in Figure 3. With all road followers transversely mounted on a rigid beam (so as to be free of any significant vibrations) various measures of rut depth can be obtained simply from the difference in elevation indicated by any combination of three road followers. In the absence of any well-defined measures of rut depth, the proposed system will be outfitted with the three additional sensors shown so that the various measures of rut depth can be determined and evaluated in the course of the project testing. These measures would include:

- Center measure (The average wheeltrack depth defined relative to the between-wheeltrack height)
- Left and right wheeltrack measures (The wheeltrack depth relative to the line extending from the center to the outside measurement point on each side)
- Overall measure (The wheeltrack depths relative to a line extending between the left and right outside points)

The road-follower sensors needed for measuring rut depth do not require the same precision as with the profile measurements. Although a distance accuracy of 0.02 inches is still desired for compatibility with the profile sensors, the measurement bandwidth can be much lower. Current practice for measurement of rut depth is normally based on average measures over a road section length of 10 to 20 feet. Therefore, the rut depth sensors could have a frequency response as low as about 25 Hz and still be capable of detecting the appropriate changes in road elevation.

To monitor the vertical motions of the vehicle body, one or more accelerometers must be used. In order to avoid errors from roll of the vehicle body, one accelerometer is required for each wheeltrack profile being measured. (It might be noted that the accelerometers are not needed for rut depth measurement purposes.) The accelerometers should be selected with two important criteria in mind. First, the accuracy of the accelerometers (resulting from the combination of hysteresis, resolution, precision, etc.) should be representative of the higher quality equipment available today, so that the long wavelengths are well reproduced. Secondly, the accelerometers should have minimal cross axis sensitivity in order to avoid excessive error in the profile arising from lateral vibrations of the vehicle body.

The transducers used for speed and distance measurement can be any of a number of available choices. The speed should be measured continuously and accurately. Distance measurement is also important, as it establishes the registration of the profile with distance along the road. Although fifth wheels have been used for speed and distance measurement in some of the earlier commercial profilometers, measurements directly off of a wheel of the vehicle can be accurate with proper maintenance of the tires on the vehicle. That method will be used in this profilometer, utilizing the FHWA-provided hardware if sufficiently accurate.

Static cross slope can be measured if a gravitational reference is available. The FHWA-owned Humphrey system will be installed in the profilometer for this purpose.

2.2.2 Signal Conditioner

The second major component shown in Figure 2 is the signal conditioning box. The signal conditioner serves as a source for excitation voltage to the various transducers, amplification to provide signal levels appropriate to the digitizer, and analog means for filtering the signal prior to digitization in order to avoid aliasing. Two types of signals pass between the computer and the signal conditioner, as shown. The data lines represent information from the transducers either acquired during a test, or during calibration and setup. The control lines are the means by which the computer communicates with the signal conditioning system. These lines carry information by which the computer sets the functions within the conditioner (setting filter frequencies, calibration modes on various channels, gains, etc.), and they carry the computer generated signal which is substituted for the transducer when the electronic components are being calibrated.

2.2.3 Computer

A computer supplemented with a number of special features serves as the heart of the profilometer system. It is the interface by which the operating personnel control the system, while the computer does most of the detailed work. The computer (via its software programs) controls the calibration and setup of the system, takes in and stores the data during test operations, and serves as the means by which raw and processed data can be output from the system.

2.3 Hardware Description

The data acquisition portion of the profilometer is diagrammed in Figure 4. All major components and their costs are given in Table I. The left column gives the nominal list prices, while the right column indicates the University costs applicable to this project as a result of educational discounts available. The system consists of four main sub-assemblies: computer, expansion chassis, tape recorder, and analog signal-conditioning unit. The following section describes the key parts of the system.

2.3.1 Computer

An IBM PC was chosen as the central control element, because it is readily available (two to three million units sold), well documented, supported by a host of hardware and software vendors, and relatively inexpensive. Although an industrial or "mini" might be better suited in terms of computational speed, an IBM PC is easier to purchase, has a vast support base, and is easier to repair. In addition, it could allow the profilometer user to compare, correlate and archive summary statistics on a popular office computer system.

System Unit - The system unit is the core of the IBM PC. It contains the system board, five expansion slots, the 8088 microprocessor, a floating point coprocessor, read-only memory plus 256K bytes of read/write memory, and power supply. The IBM monochrome display is a high quality, high resolution CRT which when used with the Hercules graphics card, will display all

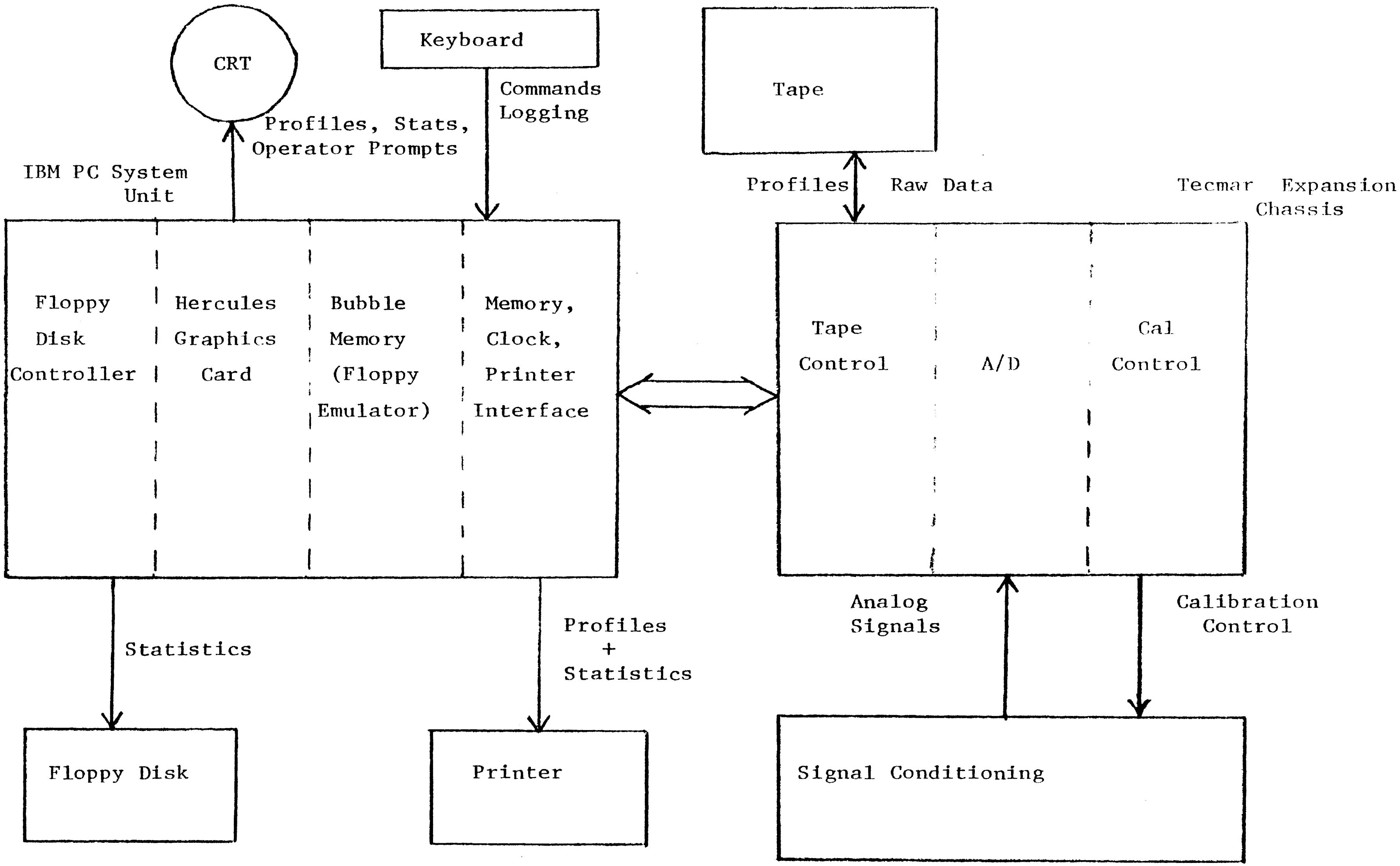


Fig. 4 Diagram of data acquisition system

TABLE I - List of Hardware Costs

	List Price	UMTRI Price
Computer		
IBM PC with 256K memory, 2 DS DD floppy disc drives and monitor	3278	2458
IBM software (DOS 2.1 and Fortran)	410	308
Documentation manuals	215	161
Hercules Graphics Board	360	360
AST Six Pack Plus 384K memory, clock serial port, parallel port	550	550
Data Translation Analog I/O DT-2801-A	1345	1345
Data Translation Screw Terminal Panel	149	149
Tecmar Expansion Chassis	945	945
ADIC Model 550 Tape System	3900	3900
Case of 5 formatted tapes	225	225
Epson FX-100 Printer and Cable	765	765
Floating Point Processor	225	225
Hicomp 512K Bubble Memory	1495	1495
	13,862	12,886
UMTRI Analog Signal Conditioning Unit		
Amplifiers, anti-aliasing filters calibration control	3500	3500
Power supplies, cable, connectors, enclosures	1000	1000
Inverter	1000	—
	19,362	17,386

operator prompts, summary statistics, and profile information. A dot matrix printer is also included for hard copy output. An AST Six Pack Plus board provides an extra 384K of memory, a battery backed-up clock/calendar, and a printer interface. The system unit also includes a floppy disc controller board, floppy disc drive, and a Hicomp bubble memory board. The bubble memory board (acting as a floppy emulator) serves as a very reliable storage device for programs, documentation, and small data sets. When the system is in the hands of the user, the floppy disc is only used when summary statistics are to be generated for transfer to another computer.

Expansion Chassis - The Tecmar PC-Mate Expansion Chassis adds six expansion slots to the IBM PC. It includes a heavy-duty power supply, built-in fan, and fully buffered address, data, and control lines. The tape controller board, A/D board, and analog control board occupy slots in this chassis.

The Data Translation DT2801-A, a low cost, high performance data acquisition board, provides the A/D interface to the profilometer sensors. The DT2801-A has an onboard microprocessor which controls analog-to-digital converter frequency, error checking, and the direct memory access interface to the PC. It includes a 12-bit A/D converter with sixteen channels of single ended or eight channels of differential input, software programmable gains, and two channels of D/A output. With a throughput of 25,500 Hz, it can digitize nine channels of data (e.g., height sensors, accelerations, gyros, and speed) in approximately 300 microseconds. Since sampling at 3-inch intervals at 55 MPH is equivalent to 322 Hz, the phase shift due to sampling skew can be ignored.

The analog control board is the only part of the digital system that cannot be purchased. It will be designed at UMTRI and wired on a prototyping card. This board provides the control signals to the analog signal-conditioning unit that switches calibration relays, automates offset adjustments, and provides other self-diagnostic functions. It also includes a system timing controller (AM 9513) which provides the correct trigger signal to initiate A/D conversions and software programmable clocks to control the cutoff frequency of the anti-aliasing filters.

2.3.2 Tape Recorder

Since approximately 126K bytes of storage is needed for one mile of single-track profile data, a floppy disc is not large enough to accommodate more than several miles of operation. The ADIC (Advanced Digital Information Corporation) Data Library Tape System is ideal for this task. This tape system has a capacity of 64 megabytes (approximately 500 lane-miles of information) that appears to the IBM PC as four 16 megabyte hard discs. The disk emulation eliminates the need for any special tape software by allowing the program to access data with the standard operating system calls. The Data Library consists of an IBM interface, a 3M tape drive (the same drive used in the UMTRI Data Acquisition System), and power supplies. The two principle components of the 3M tape, a drive module and controller module, have their own microprocessors. The drive module has a stable baseplate that allows repeated, accurate positioning of the cartridge, a microprocessor controlled digital speed servo, read/write electronics with digital gain control, and stepper motor head positioning. The digital design eliminates all potentiometric adjustments. The controller module includes a fully buffered (dual 1024 byte I/O buffers), asynchronous parallel interface. The controller issues motion commands to the drive module, positions the tape to the correct record, formats the data block, adds CRC error correction frames on write, performs error detection and correction on read, and keeps track and skips over bad blocks on the tape. The system does several self-tests and adjustment procedures automatically on power-up and cartridge insertion. This system has proven to be a convenient and reliable mass storage device.

2.3.3 Analog Signal Conditioning

The computer should be strongly coupled to the analog signal conditioning. It should provide offset and gain control and thorough calibration and diagnostic functions. The simplest way to achieve these goals is to use the analog cards employed in UMTRI's data acquisition system. The analog unit is made up of a backplane, a control card, and the appropriate number of amplifier cards (8 for a full profile and rut depth system). The control card provides address decoding and generates the control signals that are supplied through the backplane to the individual cards. All transducer inputs and amplifier outputs are routed through the backplane (see Figure 5).

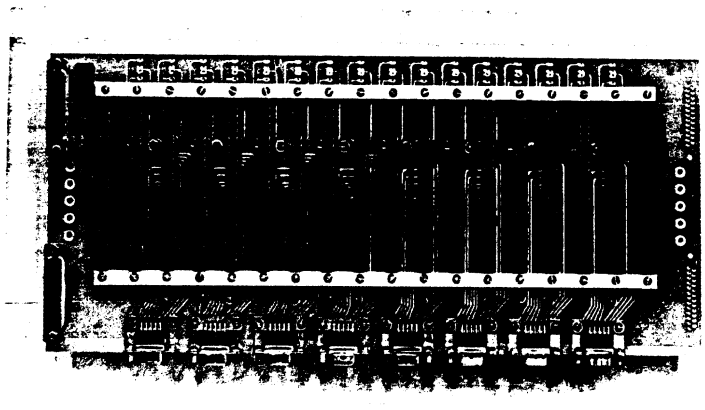


Fig. 5 Photograph of analog backplane

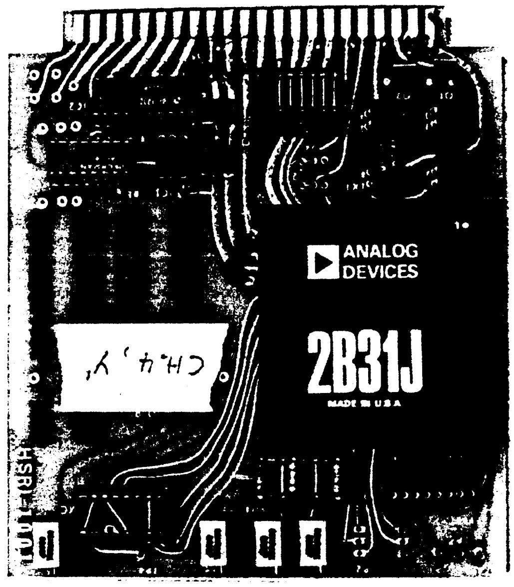


Fig. 6 Photograph of signal conditioning card

A signal-conditioning card is shown in the photograph in Figure 6 and is diagrammed in Figure 7. The primary component is an Analog Devices 2B31 signal-conditioning module (all components within the dashed lines). This module contains a high performance instrumentation amplifier with input protection to 130 volts RMS, a buffer amplifier, and a precision excitation regulator. The other components provide automatic calibration capabilities and flexible gain and transducer configurations. The transducer is linked to the card via a nine-pin connector and an I/O dip header. Jumpers on the header provide transducer excitation (+- 15 volts for servo accelerometers, and 0 - 10 volts with remote sense for strain gages and potentiometers) and routes the transducer output(s) through the cal relay to the instrumentation amplifier. By switching the calibration relay, the computer can disconnect the transducer from the amplifier and apply a D/A generated calibration signal to the amplifier input. The process permits the computer to measure the offset, gain, and linearity of each signal-conditioning card. In addition, an 8-bit D/A on the card provides a computer-generated signal to cancel any transducer or amplifier offsets. In place of the three-pole Butterworth filter currently on the card, a computer programmable 4-pole filter will be implemented. This permits the computer to change cutoff frequencies when the operator selects the nominal vehicle speed for test.

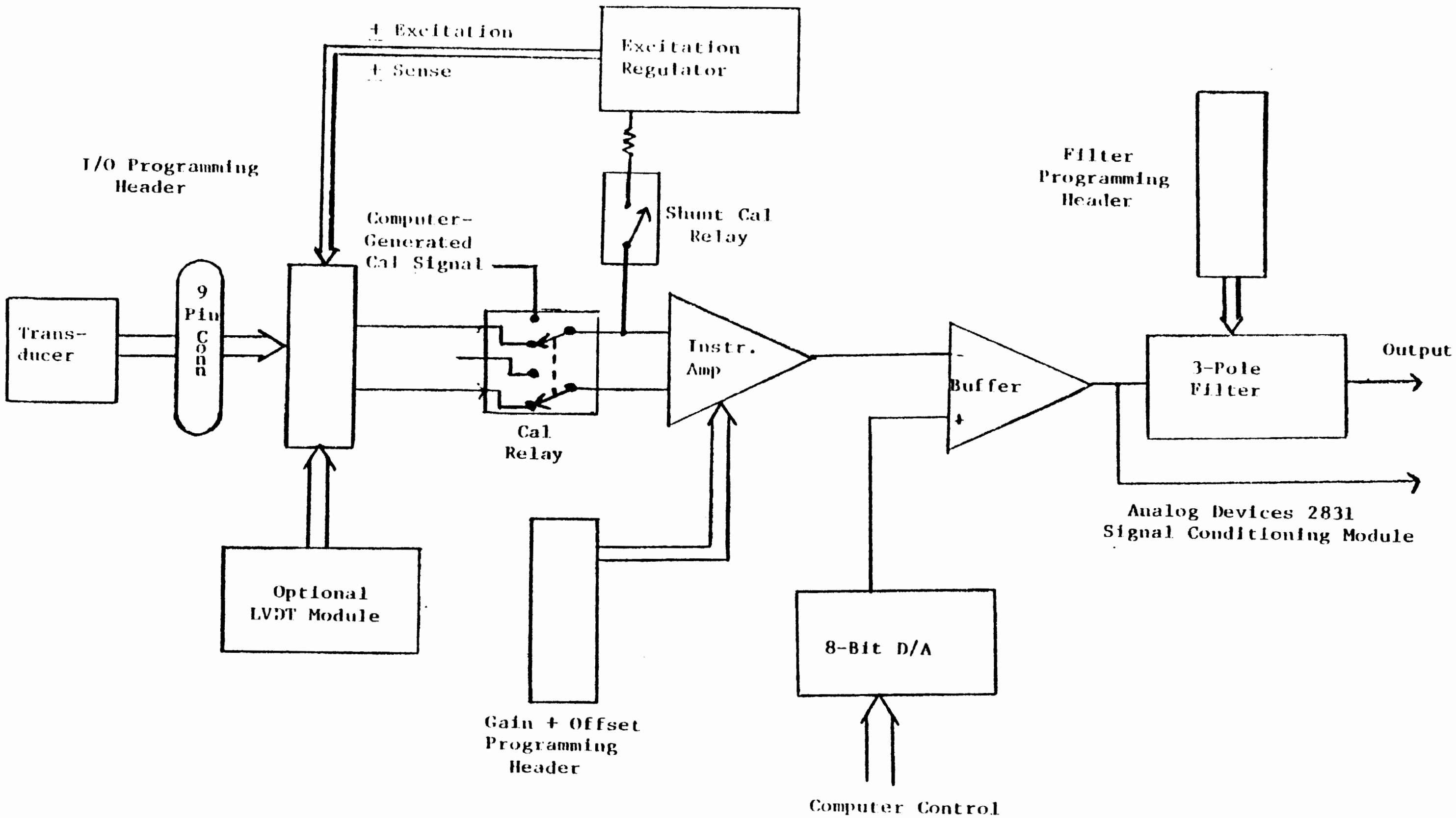


Fig. 7 UMTRI signal conditioning card

2.4 Software Description

Figure 8 shows the main software elements of the profilometer program. When the power is turned on, several diagnostics located in the basic input/output system ROM (BIOS) are executed. These diagnostics test and exercise the 8088 processor, system RAM, read-only memory, interrupt controller, DMA controller, disk controller, and keyboard. At the same time, the microprocessors in the tape system perform their own diagnostics and report the tape system status to the main computer. If all tests are successful, the profilometer program is automatically loaded from the bubble "floppy," and its execution begins. The program will then perform further tests of the hardware. Identical check files on the floppy and the tape are compared to each other to ensure proper mass storage operation. Next, the analog subsystem will be initialized and tested. Finally, a sample profile will be loaded from tape and a summary statistic will be calculated and compared to a stored value. This exercise validates the operation of the floating-point processor and the integrity of the profile program. On completion of the diagnostics, the operator is asked to validate the current date and time and the main menu is displayed. From the main menu, the operator may select any one of three sub-menus: utilities, test, or data reduction.

2.4.1 Utilities

The utility programs provide a user-friendly interface to the operating system (DOS) commands. They allow the operator to

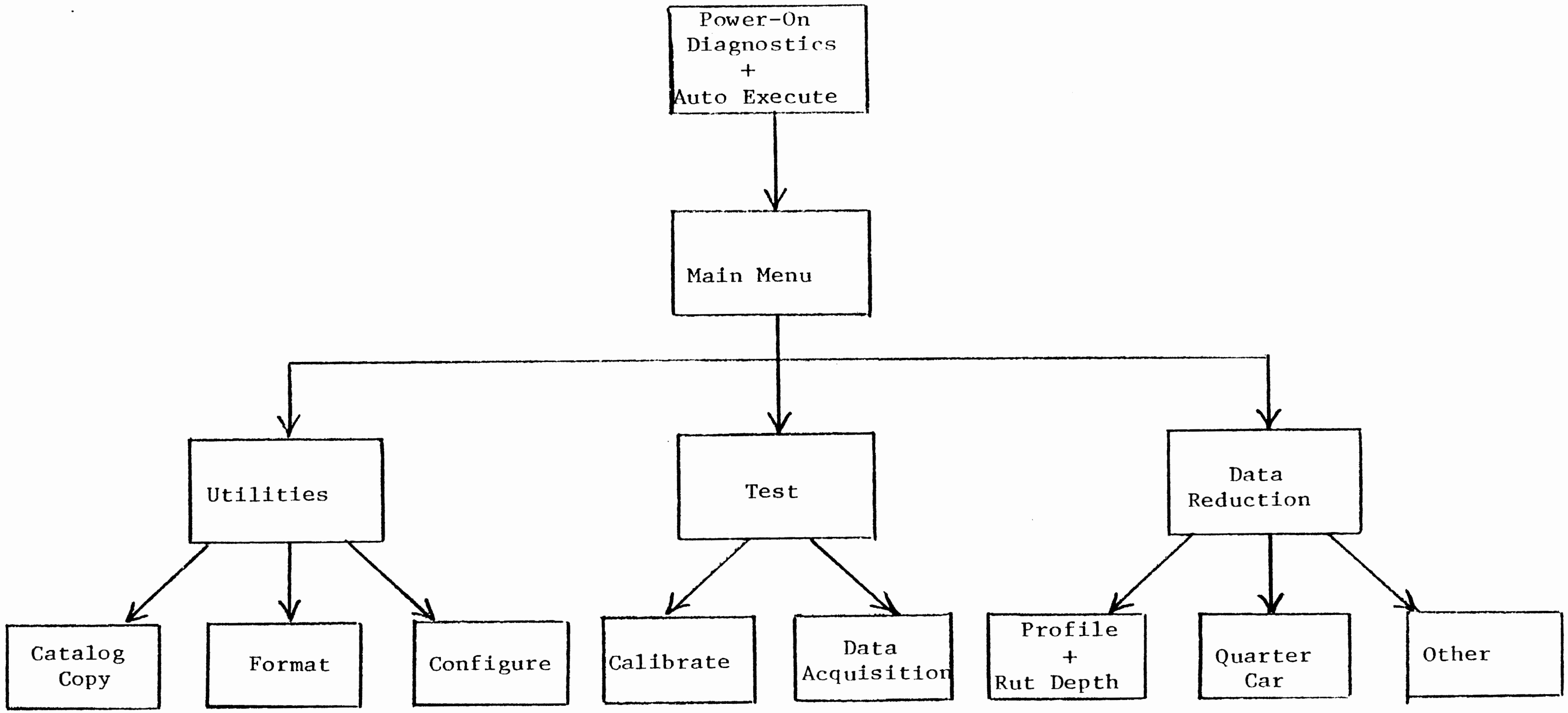


Figure 8. Main Software Elements

format tapes and disks, transfer files from one device to another, list a catalog of all data or statistics files to the screen, printer or file, and perform other overhead related tasks. Where appropriate, these routines may be also called by a test or data reduction program (e.g., when the test program discovers an unformatted tape). In addition, the utilities will include a program that permits the operator to reconfigure the profilometer system. The program allows insertions or deletions from the equipment table which indicates which and how many transducers are currently in the system.

2.4.2 Test

The test menu enables the operator to calibrate the analog system and transducers, or to acquire profile, cross-slope, and rut-depth data. The program will keep a record of when calibrations are performed and will not allow data acquisition to begin unless a calibration has been executed recently. Thus, on power-up, a calibration is automatically indicated. The operator may perform all, or a subset, of the calibration routines more often if operating conditions warrant it.

The calibration exercise consists of two distinct activities. First, the analog signal conditioning is thoroughly checked, and secondly, a physical calibration of the transducers is performed. The signal conditioning is tested and adjusted without operator intervention. The computer reads all channel offsets and automatically nullifies them. Next, an eleven-point staircase waveform is applied to the inputs of all the amplifiers, and all gains and linearities are recorded. Finally, a step input is applied and the output is checked to validate proper anti-aliasing filter operation. The programs that accomplish most of these tasks already exist (used in the UMTRI Data Acquisition System) and will be tailored for this application. After the electronics have been checked, the transducers are calibrated. This process is discussed in the next section. The data obtained from these tests are stored on disk and compared to previous calibrations (a nominal calibration table) to determine possible faults and long term drift conditions. All calibration data will also be recorded on tape with each test data set.

When a calibration has been performed, the data acquisition menu is displayed. The normal combination of transducers that will be functional during test are displayed (e.g., two track profiles and rut depth), along with the data collection mode. The operator then has the option to make changes if desired for some reason. The first data collection mode does not store the raw profile data on tape. Figure 9 shows how the mode operates. The A/D via DMA (direct memory access) fills the memory buffers with raw data. When a buffer is full, the raw data in that portion of memory are reduced to profile, rut depth, and/or cross slope measures and the results are stored. This buffer can then be used again by the A/D to store raw data. Since the data reduction takes more time than the collection, this process cannot go on forever, but must be terminated when the A/D has no empty buffers to fill (or the test is otherwise completed). Table II gives the storage

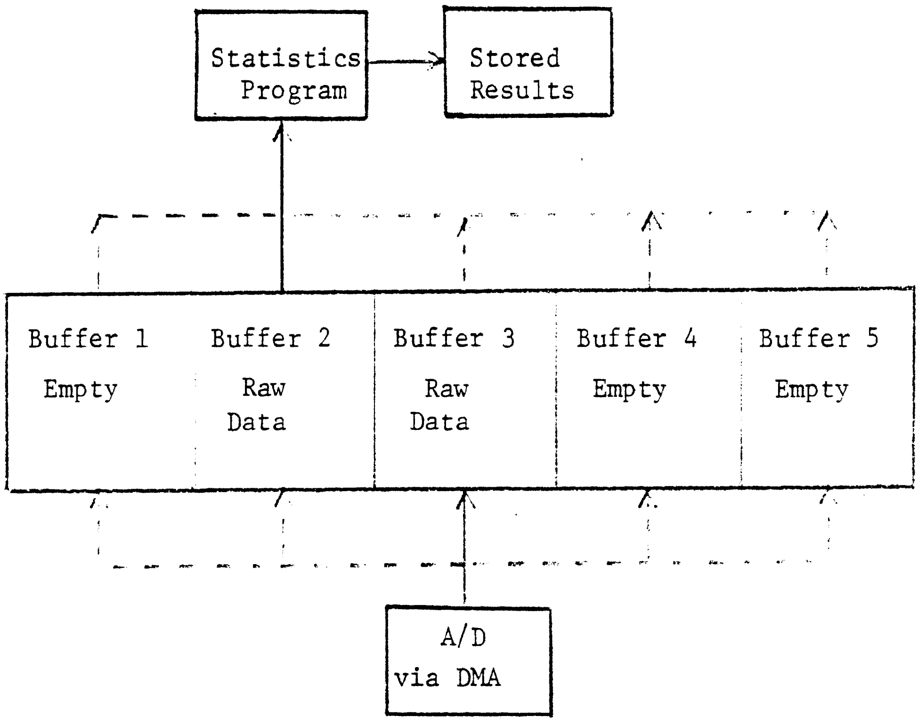


Figure 9. Mode 1 Acquisition

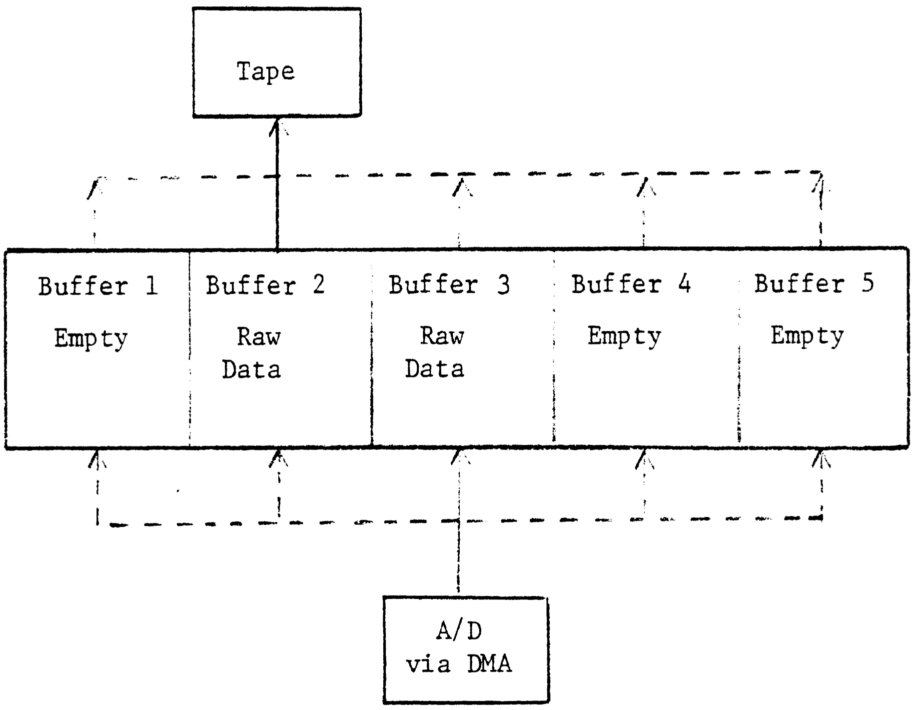


Figure 10. Mode 2 Acquisition

TABLE II - Data Storage Requirements

Configuration	Storage Requirements Bytes/Mi	Megabytes/100 Mi
One track profile	126,720	12.67
Two track profiles	211,200	21.12
One track profile + rut depth (1)	211,200	21.12
Two track profile + rut depth (2)	337,920	33.79
Two track profile + rut depth (1) + cross slope	337,920	33.79
Two track profile + rit depth (2) + cross slope	380,160	38.01

(1) One rut depth, requiring two acoustic sensors
(2) Two rut depths, requiring three acoustic sensors

requirements of the different profilometer configurations. At this preliminary design stage it is not possible to predict precisely what the length of test will be for any given number of transducers. However, with a total buffer size of 320K bytes, a minimum of one mile of data can be collected in this fashion, with a good possibility that much longer lengths are possible. The exact duration depends on the number of transducers, the types of statistics being calculated, and the speed of the vehicle.

In the second mode of operation the raw signals are recorded on tape. This mode, as depicted in Figure 10, operates somewhat like the previous mode. The A/D fills the buffers with raw data and when a buffer is full it is not reduced, but is transferred directly to the tape. The rate the A/D fills these buffers is a function of the sampling distance (normally 3 inches), the vehicle speed, and the number of transducers sampled. For two-track profiles and rut depth at 55 MPH, this rate is 5162 bytes per second. The rate at which the tape recorder can empty the buffers determines the duration of the test. This rate is a function of the average computer-to-tape transfer hardware rates (35K bytes per second) and the amount of time the operating system software takes to perform the overhead operations. If this rate exceeds the A/D input rate, then a test can last until a segment of the tape is filled (approximately 20 - 30 miles). Again, the precise test length cannot be determined in this preliminary design stage.

Once the mode is selected, the operator indicates the approximate duration of the test in miles and the program verifies that enough tape is available. Log information such as test ID, location, road type, speed, and comments are entered at this time on the tape. The test begins when either the operator responds to a prompt by pressing any key or when the driver pushes a remote start switch.

2.4.3 Data Reduction

The data reduction menu indicates the options available to process previously recorded raw data. Either the last data acquired or any previous test on the current tape can be reduced. One option calculates the elevation, rut depth, and cross slope profiles and displays the result on the CRT or the printer. A portion of these data can also be transferred to a floppy disk for transport to other data analysis sites. The second option is the computation of summary statistics (quarter-car, etc.). Benchmarks of the quarter-car program have been run on an IBM-PC with a random profile input. The results indicate that it will take approximately one minute per mile for reduction of two-track data to summary statistics. Other summary statistics, when specified, will be added to the menu. The results from the data reduction programs will be displayed on the screen and tabulated in a file for future use.

2.5 Functional Description

A better appreciation for the system of hardware and software proposed above is obtained by describing how the system will operate. The operations can be divided into three categories:

- Power-up and calibration
- Testing
- Data reduction

2.5.1 Power Up

The first stage in the use of the profilometer system is powering-up and calibrating the instrumentation. When the system power goes on the computer system goes into a self-check mode verifying that all memory and the CPU is functional. Concurrently the tape recorder system goes into its own set-up and diagnostic mode in which it aligns the heads for proper tracking on the tape, as well as checking its own electronics. On completion of the computer's self-check, it automatically "boots" a software program stored in the bubble memory, causing it to enter a diagnostic mode, checking that each channel of the signal conditioning equipment is functional and within nominal ranges. In this check the computer would verify that the primary transducers had circuit continuity with the signal conditioning. At this stage, the computer will also interrogate the tape recording system to confirm its functional status. If all hardware is functional to this level, the system continues on the power-up procedures. If, however, any malfunctions are detected, the operator is informed of which system has a problem and a recommended action is provided. In some cases the recommended action may be an operator action (checking that an instrument is receiving power), or in more complicated cases, recommending that the instrument be checked by qualified personnel.

When it is confirmed that the system is functional within the static capabilities represented above, the computer would call for a calibration of each data channel. This calibration will require operator interaction which will be guided by prompts on the monitor screen. Calibration of the accelerometers and road follower systems will be mandatory following a "cold" startup, inasmuch as this is a minimum level for good practice. Calibration procedures for the vertical gyroscope cannot be specified at this time. In contrast, calibration of the distance/speed system can be offered as an optional task, since it is more time consuming and being a simpler system is less subject to misadjustment errors.

Calibration of the accelerometer system is achieved by turning the accelerometer over (a negative gravity condition), and prompting the computer with a key press (i.e., with instruction to "Press Return when the accelerometer is on its flipped") when the condition is established. Up to four steps will be involved with this calibration representing the zero- and one-G condition on up to two accelerometers. The calibration values will be obtained by observing and averaging the transducer output for a period of a several seconds in order to eliminate spurious errors due to vibrations of the engine, if running, or movements of the operating crew.

Calibration of the road follower transducers is accomplished in a similar manner, although by placing reference surfaces under the transducers. In this case, it is essential that the vehicle body be essentially stable during the calibration. That is, the crew member cannot climb into and out of the van to position the reference surfaces, as the change in static height on each entry and egress will contribute errors to the calibration. Thus for road follower calibration, the computer will monitor for placement of the reference surfaces, prompting the operator with a sound when an acceptable reading is obtained with each. The computer can also monitor for movements of the vehicle body via the accelerometers or the other road follower transducers during this phase of the calibration to ensure that no spurious movements will invalidate the calibration. Calibration of all of the road follower transducers will be carried out in this fashion.

The calibrations (gains and offsets) that are obtained on any particular occasion will be compared to previous records, to identify if a significant change has occurred, suggesting a problem with one of the transducers. When such a change is observed the operator will be informed of the discrepancy, both as a warning that the system may not be operating correctly at this time, and also to warn that records from the previous test period may not be valid.

The calibration of the distance and speed measuring hardware is obtained at running speed on the highway. As a part of the operational procedures it will be necessary for the crew to establish and mark a measured distance along a major highway in the vicinity of normal operations. A minimum distance of one mile is required. For calibration, the crew drives the profilometer along this section at selected speed which has been entered into the computer. The crew is prompted to enter into the computer a "start" and "stop" input at the beginning and end of the section. The system will then automatically determine the average travel speed, and provide the crew with an indicated speed that will correspond to the desired speed, thus providing a calibration of the speedometer. The speed, however, is not as important as the distance calibration which is the basis for sampling points along the pavement and determining the precision velocity data needed for profile computation. The distance calibration will be determined for the site and compared to previous calibrations as a check for errors. Thence, the new distance calibration will be used until superseded by another calibration. The distance calibration will be identified by date, and such information will become a permanent part of each test record.

2.5.2 Testing

During testing the operation of the system is largely automatic, requiring only that the crew enter certain information defining the tests desired. For record keeping purposes, of course, this information must include the test site identification. The date and time are provided by the system from its internal clock/calendar. The planned test length will also be requested, as it will provide a means to optimize the file system. In the absence of a crew response on test length, the file with the maximum remaining capacity will be allocated for the test. The beginning of test will be denoted by a keyboard command to the computer. The test will proceed until a "stop" command is issued by the crew, or in its absence, until the recording and data buffers are filled. On longer tests, the crew will be given the option of entering milestone points as reference to their location on the test section. Milestones will be denoted by a numerical value that will be injected into the data at the point where it was "marked" by the operator. By using numerical identifiers, the crew will be able to enter alphanumeric descriptions of each milestone point when it is most convenient for them (i.e., it is not necessary to enter the description prior to the marking point).

2.5.3 Data Reduction

In the second mode of operation, the raw accelerations and road sensor signals are taken into the data acquisition system. Though scaled to engineering units, they are not reduced to profile during the test process. At the completion of a test the operator has the option of reducing data from that test or from prior tests. On the occasion of the first reduction of raw data, a profile is calculated and substituted in the record for the raw signals. Also rut depth and cross slope profiles are calculated and stored similarly. The records are then marked accordingly to indicate that they are reduced when they are accessed again at any future time. A number of other options for data reduction are also available to the operator for computation at the same time. These include the computation of summary roughness numerics and summary rut depth data. If these options are exercised, the computed values are also stored on the permanent (digital magnetic tape recording). This data reduction mode will take a time period approximately equal to that required for the test. For immediate use, the operator can also direct the summary data to the floppy disk system to be recorded along with test identification information. Thus the summary data can be immediately transported from the profilometer on the floppy disk medium to an office computer system for additional analysis. On the other hand, the permanent profile records on the digital tape can be placed in archives if so desired, or the records can be discarded (erased) and the tape reused. By placing the summary data on floppy disks, it is most convenient for the highway organization to perform additional analysis such as:

- Searching the records for sites most in need of maintenance.
- Compiling statistical properties (means and standard deviations) of the roads that were tested.
- Maintaining records of network tests to date, and scheduling future tests needs.

3.0 PROFILOMETER CORRELATION PLAN

For planning purposes, the Profilometer Correlation Program may be divided into four sub-tasks. The content and plans for each sub-task are described in this chapter.

3.1 Preparations for the Correlation Program

The preparations for the correlation program involve the experimental design, selection and arrangements for the participants, and selection of the test sites.

3.1.1 Experimental Design

The purpose of this experiment is to determine the limits of valid profile measurement for the FHWA profilometer built under this project, and its comparison to the various other road profilometers available to highway departments in the world today. The validity of any profilometry method depends on the purpose for which the measurements are made. A most important application today is the calibration of response-type road roughness measurement systems (RTRRMS), requiring accurate measurement over the waveband range important to highway vehicles. Beyond this they are used to measure a pavement profile that is subsequently analyzed for different purposes, each of which places its own demands on accuracy and waveband range. Therefore, the first objective is to assess the adequacy of each profilometer for calibrating RTRRMS, and the second objective is to evaluate the range of measurement validity (speed, roughness levels and waveband spectrum) for each profilometer, identifying, where possible, the functional differences between the systems limiting their performance.

The experiment is accomplished by having each profilometer system measure a series of selected road sites, providing copies of the measured profiles (or reduced versions thereof) to the UMTRI staff for subsequent analysis. On a selected subset of the sites, rod and level measurements of the wheeltrack elevation points will be obtained for comparison with the measurements obtained from the profilometers. The comparisons which will form the basis of the results from the experiment are described in the later section on Analysis.

The meeting will be a three-day program. The three-day program allows one day for getting the participants oriented, a second day for testing, and a third for retests or reviewing data. The date which is first choice for the program is Tuesday through Thursday, 11 - 13 September 1984. The second choice would be the following week on the dates of 18 - 20 September.

3.1.2 Selection of Participants and Arrangements

It is anticipated that only profilometers capable of measuring profiles and/or statistics computed directly from the longitudinal profile will be included in the program. Although summary statistics (such as the Inches/Mile obtained from a quarter-car simulation), that may be available from the different systems, will be acquired as a part of the project data, a recorded profile will also be required from profilometers having this capability for UMTRI analysis. If the participating systems do not record profile, then details of the analyses will be required. Analyses that are not unduly time consuming will be applied to rod and level measures to validate these systems. The options for recording media (analog and digital tapes, and disks) compatible with UMTRI hardware will be identified to facilitate the transfer of data. The possible candidates for participation in the program are as follows:

- FHWA profilometer being developed at UMTRI
- GMR-type Inertial Profilometers available at
  - The Pennsylvania State University
  - Ohio DOT
  - West Virginia DOT
  - Texas DOT
  - Michigan DOT
  - Minnesota DOT
  - Kentucky DOT
  - South Dakota DOT
  - GM Proving Grounds
- Swedish Roadmeter (at Novak, Dempsey & Associates)
- ARAN
- Air Force Laser Profilometer
- TRRL Laser Profilometer
- French LCPC APL

On approval of this Plan, the UMTRI staff will immediately forward to FHWA a draft letter of invitation along with an announcement for the program. The announcement will contain an explanation of the program objectives, schedule, data requirements, and details on accommodations for those who would participate, and in total the materials should be adequate for the FHWA to make the initial contacts with the states regarding the invitations. The UMTRI will send similar letters and information to those organizations listed above, exclusive of the states.

In the initial contacts with the participants, the identification of personnel at UMTRI will be provided so that individual contacts can be made to answer any questions by the potential participants. Prior to the meeting, an additional letter will be sent to the participants providing them with further instructions as the details of the program become more defined.

3.1.3 Selection of Test Sites

A series of approximately 20 road sites will be identified for testing in the program. All will be paved roads of the bituminous and Portland Cement Concrete (PCC) types. Most of the sites will be on public roads in the South East Michigan area selected from those used in the RTRRMS Correlation Program described in the NCHRP Report #228. Efforts will be made to obtain access to about 6 sites on a proving ground in this same area. Proving ground sites are desirable in that they provide locations where traffic can be controlled quite easily, thus facilitating testing, and the rod and level measurements of profile for comparison to the profilometer measurements. The GM Proving Ground staff has taken an interest in this program during an earlier contact, and once FHWA approval for the program is obtained, GM will again be contacted for the purpose of obtaining formal commitments for the use of the Proving Ground. In the event GM cannot be used, the Chrysler Chelsea Proving Ground will be considered as the second choice.

From the technical standpoint, the selection of sites will parallel the logic used in selection of the NCHRP sites. That is, the sites should provide roughness typical of actual roads, while representing roughness levels covering the spectrum from the smoothest available in this vicinity, to roughness levels typical of roads in need of repair. The sites should be distributed uniformly over the roughness range so that it will be possible to establish the performance limits of profilometers that experience malfunctions on high levels of roughness (such as road follower wheel bounce with the older GMR-type Inertial Profilometers). At the same time, the sites should cover as many different qualities of roughness (cracking, faulting, tar strips, bridge crossings, potholes, patches, etc.) to identify conditions where some of the instruments may produce erroneous data.

A preliminary selection of sites will be made from the knowledge of local sites obtained in the NCHRP program, and the information that can be obtained from the Proving Grounds staff. Prior to the program, the FHWA profilometer will be used to test the candidate sites, including those on the Proving Grounds, to verify the acceptability of the sites, and to establish test procedures. Where appropriate, the test sites on the public roads will be marked with benchmarks in the form of roadside signs to identify for the participants the beginning and ending locations of each site.

3.2 Conduct of the Experiment

Approximately one month prior to the program, a second letter will be sent to all participants providing additional information on the program, and including instructions and auxiliary information that will be helpful to them in planning their stay in Ann Arbor. The UMTRI staff will be available to aid participants in the arrangements for accommodations and facilities for their equipment. The program will be staged at UMTRI making available the garage, conference rooms, and electronics and mechanical support staff to the participants.

The participants will be requested to arrive in Ann Arbor on Monday, 10 September, and to come to the Institute for an orientation meeting on Tuesday morning. Preliminary tests will be scheduled for Tuesday afternoon to familiarize each participant with the planned test methods, and uncover any problems that might arise. Wednesday will be the primary test day during which all the public road sites are covered by testing in convoy fashion. Tests at the Proving Ground will be scheduled on Thursday morning, leaving Thursday afternoon for any retests that the participants might choose to do. Although the program will officially end on Thursday, if any of the participants care to, they will be able to stay over until Friday to complete any testing or data reduction necessary.

In the same time frame as the program, UMTRI will arrange to have rod and level surveys made of six of the sites. The sites will cover a range of roughness, although to the extent possible, Proving Ground sites will be used because of the much better traffic control available there. On public road sites that are to be surveyed, UMTRI will coordinate with the Michigan Department of Transportation for traffic control during the survey. Rod and level measurements will be made at 3 inch intervals for both wheeltracks of the roadway. On the sites that are to be surveyed, the wheeltracks will also be marked to aid the participants in tracking the same path that has been surveyed.

3.3 Data Analysis

The data from the profilometers and from the rod and level surveys will be entered on the University's Amdahl computer system for analysis. Where summary statistics are provided from the profilometer equipment, comparisons will be made with the same statistic computed from other profilometer signals and the rod and level profile. This will establish the validity of the different profilometry methods for the purpose of measuring specific summary numerics.

The raw profiles will be analyzed to determine the power spectral density (PSD) function of profile from each profilometer on each site. The spectra from each profilometer will be compared to that of the rod and level to determine the usable wavelength range of each device. The comparative performance will be examined to identify any sensitivity to roughness level as an indicator of limits on the roughness that can be validly measured by the profilometer. Where limits are observed with one of the systems, attempts will be made to identify the cause.

The profiles will then be processed through a quarter-car simulation (QCS) to calculate the Reference Average Rectified

Velocity (RARV) statistic that was identified in the NCHRP Report #228 as a standard for calibrating RTRRMS equipment. The validity of the rod and level method for measurement of profiles adequate for determing accurate RARV values has been established in the International Road Roughness Experiment conducted in Brazil in 1982. Therefore, the degree of agreement between the RARV values obtained from each profilometer with that from the rod and level can be used to define the accuracy and range (measurement speeds, roughness range, etc.) over which the profilometry system can be used for calibrating RTRRMS.

3.4 Reporting

A draft report on the Correlation Program will be prepared at the completion of the analysis, and will be submitted immediately to FHWA. It is suggested that copies of the draft report also be sent to each participant, both as an appropriate gesture, and to provide opportunity for them to identify any errors in analysis or interpretation applicable to their equipment. The report will briefly describe the correlation program, and present a detailed exposition of the results obtained. Plots of the individual measurements will be provided to show the comparative performance of the FHWA profilometer, and each of the other participating systems. The results will be discussed with emphasis on identifying the range of validity for each system, and the cause when a limitation is observed. The range of validity for which each system can be used to calibrate RTRRMS systems will be noted.

Following the receipt of comments on the draft report, it will be revised as necessary and included as a portion of the final report on the project.

APPENDIX A

Profilometer Functions and Operating Modes

In the two decades that profilometers have been available to highway agencies, they have been put to uses that can be categorized in terms of the measurement function performed and the program mode in which they are operated. In this discussion, function is defined as the type of measurement that is obtained (i.e., measurement of a full profile vs. a summary roughness statistic). The program mode relates to the purpose for the measurement, such as network surveys for pavement management programs, or new construction evaluation. An understanding of the measurement functions and program modes is important to the designer of a new system, in order to achieve a design that will operate efficiently for the intended purposes. From these analyses the performance requirements for the system can be established. The performance requirements of interest are:

- Basic measurement capabilities (profile, rut depth, etc)
- Minimum length of individual measurements
- Turn-around time between tests, or duty-cycle
- Types of data reduction needed, and presentation methods
- Data reduction time and constraints
- Measuring speed

All of these factors are important both from the perspective of the designer and the potential user. From the design standpoint, the length of test, amount of data reduction, and time available for data reduction have a direct impact on the computational power required within the system; hence these considerations have a strong impact on the initial cost for a profilometer system. Yet for the user, the degree to which he is unconstrained by these concerns has a direct impact on ease of use and efficiency. The compromise between these factors then ultimately determines the economics of operating a profilometry system within a highway department (See Appendix C).

Measurement Functions

Historically, the two main functions that have been served by profilometers have been to measure the longitudinal elevation profile of a roadway, or to determine a summary measure of the roughness of a road section (a summary roughness statistic). The two are not mutually exclusive, and are often obtained simultaneously. Less common functions, but ones that are of interest in this project, are measurement of rut depth and cross slope along a roadway.

1) Longitudinal elevation profiles - Longitudinal elevation profile (LEP) is most frequently measured in the two most obvious wheeltracks on the highway surface. The measurement is accumulated as an analog or digital record of the elevation points along the roadway, although in the case of an inertial profilometer the elevation values are relative to a dynamic reference. Thus they are bandwidth limited and show neither the true slope nor true elevation at any arbitrary location. Nevertheless, such measurements have utility for the highway engineer in assessing the nominal roughness level as would be seen by a road using vehicle, and for other purposes.

Measurement of the LEP has been a routine function in profilometry in the following contexts:

A) Archival Records - It has been the practice in some states to keep permanent records of the LEP measurements obtained with a profilometer. The "raw" measurements contain the most information about the road, hence this type of archival record has the greatest utility for allowing the agency to go back later and examine how the road surface has changed with time. Of significance here is the need to ensure that the profilometer LEP records are validated (i.e., that a flag is set on the occasion of an invalid test so that erroneous data does not get into archival records without appropriate indication), and the need to record LEP records on a reasonably inexpensive medium.

B) Research - Profilometers often reside in the research functions of a highway agency, at least when initially acquired. In this environment, much experimentation may go on as the agency learns to use the equipment correctly, and learns the functions it can serve. In this setting LEP records are needed on a more temporary basis (the recording medium should be reusable), and for more diverse purposes. Even though operators with higher skill levels are available in the research setting, features on the profilometer that ensure that invalid tests are identified are of substantial benefit in facilitating research. For research purposes, maximum accuracy in the profile record is also desired because of the diverse purposes for which the measurements may be made. For example, the diverse uses may range from calculation of fill materials in a construction project (the Bituminous Fill Program) to tracking small changes in a localized area of a road as an indication of deterioration over time.

2) Roughness Evaluation - A common application of a profilometer is the evaluation of the roughness level of a road as would be seen by a using vehicle. The LEP itself is not of direct interest (although it is often measured and recorded if only in an abbreviated form), but rather a summary statistic. The summary values are determined from simulations of the vibrations in a quarter car model (QCS) as it is "operated" over the measured profile, or from waveband-types of analysis of the measured profile. Summary numbers are obtained, and recorded for periodic lengths of roadway varying from about 0.1 mile to 1.0 mile sections. Roughness numerics can be computed for the two wheeltracks separately, or the two wheeltracks can be combined before computing the numeric. When combined, the numeric can indicate vertical roughness (average of the two profiles), or a transverse roughness property analogous to a dynamic cross slope.

3) Rut Depth - Rut depth is measured and quantified in several ways. The purpose for its measurement is to quantify the extent of road surface wear in a wheeltrack (as for example may be caused by the use of studded snow tires), or the displacement of road surfacing material (for bituminous wear courses). The rut depth is determined by making comparative measurements of surface elevation in the transverse direction on the roadway. A minimum of three elevations are necessary, although any number

could be acquired. The rut depth is determined by analytically drawing a line across the surface coincident with the two peak readings of elevation, and determining the depth of depression at the third elevation reading. This is equivalent to defining rut depth in reference to the straight edge method. Many variations on the measurement are possible. With more than three elevation measurements from which to work, the calculation algorithm may search for the two maximum values on either side of a wheeltrack as the basis for developing the reference line; and it may search for the maximum depression among the remainder of the elevation readings. If the elevation measurements span the entire lane, the analysis method may search for as many as three peak elevation values, drawing straight lines equivalent to a string placed transversely on the surface from which to make the depth measurements. In the limited cases in which rut depth has been measured with profilometer systems, information on the rut depth is not acquired with the same level of detail as required for LEP. Specifically, the rut depth is measured as an average value over road sections that are 10 to 20 feet in length.

4) Static Cross Slope and Grade - Static cross slope is the absolute elevation difference between the left and right wheeltracks on a highway. It is comparable to superelevation, which may be characterized as an average property along a limited length of highway. Static cross slope measurement has utility for verifying the effective superelevation in the "as constructed" state of a highway, and for predicting the potential for water accumulation that may lead to hydroplaning. It has not

been measured routinely by any profilometry system in use to date because of the difficulty of establishing a fixed and level reference plane. Stabilized gyroscopic platforms are one method of establishing such a reference plane, however the expense, the constant attention required in their use, and fragility of such equipment makes it inappropriate for installation in a profilometer. Pendulums and other inertial devices drawing their reference from the gravitational gradient have not yet been developed because of the problems of the superimposed lateral accelerations in a moving vehicle which cause deviations in the reference plane. The measurement of highway grade is the longitudinal equivalent of static cross slope. When suitable cross slope hardware is developed, it is likely that it could be directly applied to measuremet of highway grade with a mobile profilometer.

Program Modes

The program modes defining the ways in which road profilometry systems have been put to use are grouped here along the lines of the pavement management needs within a highway department.

1) Statistical Network Condition Surveys - In managing the investment for which they are responsible, highway officials need to maintain a timely picture of the general condition of their highway system. Roughness and rut depth are among the recognized indicators of that condition. Thus it is a reasonable function to use the profilometer to perform periodic surveys of the

highway network. The immediate objective in the surveys may be to assess the roughness and rut depth in terms of summary numerics providing a statistical picture of the network condition The survey results may then be compiled in terms of population properties and distributions for individual routes or highway classes. The roughness may be expressed in terms of quarter car statistics or waveband values linked to any existent data base on roughness.

For this purpose 100% monitoring is not necessary to develop population statistics, thus this operating mode does not require system capability with 100% duty-cycle. From the statistical viewpoint the measurement of population means and distributions can usually be achieved with a duty-cycle on the order of 10% to 20%. On the other hand, it may often be desirable to catch measurements at specific sites for continuity in a historical record. Hence, a 50% duty cycle is probably a more reasonable minimum. Note that to obtain valid population measures there are no constraints on the length of individual measurements so long as they exceed the minimum for calculating a meaningful roughness statistic (the minimum length depends on the waveband included in the analysis). Similarly, an accurate registration of the precise road location where the measurements are obtained is not as critical in this mode, as will be seen for other modes. The speed with which the measuring vehicle is moving is important. Low speeds imply that data acquisition will take a long time, and possibly require additional manpower for traffic control during this time.

With regard to rut depth, the same guidelines are again appropriate. A sampling over 50% of a highway route constitutes a reasonable statistical base, and as a measure of overall network condition is more than adequate.

Operated in this mode there are no compelling reasons to require that data reduction be accomplished immediately after measurement. Rather the raw data acquisition may be performed in an intensive road survey effort, with the data reduction to summary statistics or population statistics performed separately. However, verification that valid raw measurements have been obtained during each test in the survey exercise is critically important for efficient operations in this mode.

2) Discrete Network Condition Surveys - A second way in which a profilometer may be used is to survey the condition of discrete sections of the road (by project, mileposts, etc.). The purpose in this case is to build a data base of measures that can be archived for reference purposes. The results may be compiled into a statistical picture as described in the section above, in addition to being stored for reference as needed in future years. The survey may be an inventory and cover 100% of all roads, or all roads of a particular type, all roads in a particular area, or some other logical sub-grouping. For this purpose it is anticipated that the full LEP should be obtained from which to build the archival data base. Though the summary roughness or rut depth information can be compiled as an option, retention of the LEP provides the opportunity for the broadest utilization of the archival data as future needs become known. In this mode of utilization, the identification of each measurement (location,

distances, dates, conditions, etc.) is more critical than for statistical survey purposes. Likewise, the duty-cycle for the measurement operation is much more important. To be most useful, the system should be capable of continuous measurement over a number of miles at highway speeds. On Interstate highways, a distance of 100 miles is attractive (a driver break every one-and-a-half to two hours being advisable for safety), and a means for entering periodic location codes during test would be necessary. On primary roads, continuous test distances on the order of ten miles are probably more typical.

Immediate data reduction again is not a critical requirement in this mode, although confirmation that valid test measurements are being acquired is a requirement.

3) Identification of Maintenance Needs - One element considered in the allocation of maintenance and rehabilitation funds is the roughness or rut depth condition of a road section, or its severity in comparison to other candidate sections. The profilometer can be used to obtain detailed information about the roughness for use in these decision processes. In the minimum application, the profilometer would be used to survey the whole length of a candidate road section determining summary roughness and/or rut depth values for subsections as a basis for deciding the level and the extent (locations) of need for maintenance. Utilizing its broader capabilities, the measurements could be used to assess the type of distress (potholes, faulting, etc) with suitable analysis of the profiles obtained. In this mode, the measurements themselves would involve only a part of the time that the profilometer was dispatched for these types of

activities, hence measurement lengths of only a few miles would be necessary, and duty-cycles of 50% would be more than adequate. Speed of measurement is seen as not critical in this application.

Immediate, or on-line data reduction, is not a critical requirement in this mode.

4) New Construction Evaluation - Profilometers can be of utility during the construction phase of a highway program, serving several purposes. Before final construction the profiles of subgrade condition have been used to estimate the amount of materials that will be required through bituminous fill calculation methods. Test lengths of a few miles with duty-cycles of 50% are reasonable in this context. Immediate data reduction is not required, inasmuch as the bituminous fill calculations can be performed at a later time to be provided to administrative agencies or contractors. Speed of the measuring vehicle is not viewed as critical.

Profilometers may also be used to monitor the roughness levels being achieved during new construction activities. Though these measurements must lag the construction process, an early result is desirable. Hence, in this mode data reduction at this site may often be required, allowing it to be communicated immediately to the construction personnel.

5) Calibrating Roadmeters - Within the United States, the calibration of response-type road roughness measuring systems (RTRRMS) from measurements of an inertial profilometer has been demonstrated. The profilometer is used to measure the longitudinal profile in both wheeltracks and a summary statistic

is computed. Thence, the roughness measurements obtained from the RTRRMS equipment are correlated to the summary statistic, such that their measurements can be directly translated onto a known scale. For this purpose, the profilometer is required to measure a series of road sites in the same time frame as measurements by the RTRRMS equipment. For maximum efficiency the profilometer should immediately process the measurements to the summary statistic level, so that the entire calibration process can be completed within the time frame of a few hours to a day. Measurements longer than 1 mile would rarely be required. Because of the transit time between calibration sites, a low duty-cycle is normally adequate.

SUMMARY

The various considerations presented in the above discussion can be summarized by a table of the functional requirements appropriate to each program mode. The table is presented below.

TABLE I - Performance Requirements for Profilometers

Program Mode	Measurement Capability LEP Profile	Summary Roughness	Rut Depth	Min. Test Length	Min. Duty-Cycle	Data Reduction Time
Statistical NCS	Opt.	Yes	Opt.	1 Mi.	50%	Not critical
Discrete NCS	Yes	Opt.	Opt.	100	>50%	Not critical
Maintenance Needs	Opt.	Yes	Opt.	1-10	50	Not critical
New Construction	Yes	Yes	No	1-10	50	Immediate
Calibrating RTRRMS	Opt.	Yes	No	1	50	Immediate

NCS - Network Condition Survey

APPENDIX B

Hardware Performance Requirements

As presented in Chapter 2 of the main part of this report, a road profilometer consists of a series of hardware subsystems, each of which must be designed with an eye toward the required performance and compatibility with the other hardware. The critical subsystems in a profilometer are the road follower, accelerometers, and data acquisition/recording systems. Each of these are discussed in this Appendix, presenting the considerations that go into their design and selection.

Road Follower

The design concept of the inertial profilometer depends on placement of an accelerometer on the sprung mass of the profilometer vehicle, with the road surface sensed from that reference point. In the original designs the road surface was sensed by a road wheel mounted below the vehicle with a displacement transducer used to detect its position relative to the sprung mass. A potentiometer is used to transduce the wheel location (rather than, for example, an LVDT because of the phase distortion introduced into the signal). In order to follow the road surface accurately, the road wheel must be very light in construction, and must be held against the road surface with considerable force. The state of the art in design results in a wheel that has a very high natural frequency (on the order of 100 Hz), nevertheless, it still introduces errors to which the operator must be alert. The major shortcomings of road follower wheels are - wheel bounce (which introduces false bumps in the profile), wheel out-of-roundness (which adds a periodic component to the profile at the wavelength equivalent to the wheel circumference), and durability (follower wheels and the potentiometers are subject to very severe vibrations that result in a limited life).

Because of these shortcomings, various organizations have attempted to develop non-contacting methods of sensing the road surface using either light or acoustic waves. A number of these have been reviewed for the purpose of determining which have performance compatible with the needs for profile and rut depth measurement. A brief description of those that have been considered is provided here.

1) K.J.Law/MDOT - Both the K. J. Law firm of Farmington Hills, Michigan, and the Michigan Department of Transportation have developed similar implementations of an optical non-contacting road follower. The system shines a rectangular beam (visible wavelengths) of light onto the road surface. Its location on the surface is detected by an optical sensing system viewing the spot at an angle to the incident light beam. The detector uses a chopper (accomplished via a rotating mirror system) to determine the location of the light spot relative to two reference points. In this way the indicated distance is insensitive to reflected light intensity (as long as it is above a minimum level). The size of the illuminated spot can be made sufficiently large that it is rarely obscured by cracks and

holes in the pavement surface. The major drawbacks with the current designs are power consumption, reliability of a system with moving parts (the rotating mirror system), and the necessity of shielding the sensor from excessive ambient light conditions.

2) Southwest Research Infrared Sensor - The Southwest Research Corporation has developed a non-contacting sensor utilizing an infrared beam. The beam is projected vertically as a circular spot on the road surface and is viewed at an angle by sensors on both sides of the projection optics. The optical sensors are configured in a Wheatstone Bridge arrangement detecting the total illumination on each of four sensors. By normalizing by the total illumination of the four sensors, and sensing the imbalance in the bridge, the distance to the surface is detected with some immunity to reflected light intensity. The Southwest IR Sensors have low power consumption and no moving parts. The reliability of these units has not been quantified, although some operational failures have been experienced in the tests of the units at UMTRI. Extensive testing and analysis during this project have shown that the design concept results in a sensitivity to surface reflectivity (reflected light intensity), that can potentially lead to significant measurement errors.

3) Selcom Infrared Sensor - The Swedish Selcom organization manufactures a line of infrared distance detectors that have been used by VTI as non-contacting sensors in a road profilometer application. The Selcom

sensor projects a narrow beam of light reflected onto a linear analog detector. The detector acts like a voltage divider from which the distance is determined. In limited tests at UMTRI, no sensitivity to surface reflectance was observed, except in the case where the light level dropped below the threshold of the detector. With the small light spot, the Selcom sensor is more prone to signal dropout when the light beam falls in holes or cracks in the road surface. The system has no moving parts, and includes a fairly sophisticated signal conditioning system to preprocess the distance signal.

4) Pulsed Wave Acoustic Sensor - Polaroid, the K. J. Law firm, Massa, and other organizations have developed non-contacting acoustic sensors operating on the pulsed wave principle. A short burst of ultrasonic sound is emitted from a transducer and the transit time until the return wave is received determines the range to the target. Such devices have been used to detect road surfaces in both high speed and low speed roughness measurement applications. With typical standoff distances of one foot, approximately two milliseconds are required for wave travel. With allowances for wave detection and a quiet period between measurements, these devices are limited to a sampling frequency of approximately 100 Hz. In addition, ambient noise and variations of the sound velocity in the turbulent air in the vicinity of a vehicle can cause errors in the measurements obtained.

5) Continuous Wave Acoustic Sensor - A continuous wave acoustic sensor has been developed by Ensco for the purpose of non-contact surface detection. A continuous ultrasonic beam is emitted by a transducer and the phase relationship of the return signal is detected for the indication of range. As designed, the system was subject to ambiguity errors when the phase angle passed through 0 or 360 degrees, limiting its range to less than that needed for profilometry purposes. Although methods for solving this problem exist, the system was never developed to the point of utility in profilometry applications.

Each of the above transducer methods has been used with varying degrees of success in the remote sensing of a road surface. The three optical types and the continuous wave acoustic sensor have been used in high speed profilometry. The pulsed wave acoustic sensor has been used for low speed measurement, and is now being used by K.J. Law in a roughness measurement system (which, however, does not measure the longitudinal elevation profile for recording purposes). All of the sensors have at least one recognized shortcoming, hence there is no single choice that is without reservation. In addition, the choice should take into account the availability on the commercial market, purchase cost, and the differing performance requirements for profile versus rut depth measurement.

For profile measurement, studies at UMTRI have indicated that a profile resolution to 0.020 inches with measurements at least every 3 inches (about 300 Hz sampling frequency at 55 MPH) along a road are sufficient for discerning roughness at a level of detail for predicting virtually any vehicle vibration response (The quarter-car can be used with longer intervals, up to 2 feet for higher speeds and most road conditions, but the shorter interval is needed for certain road surface types.) For measurements directly from the sprung mass of a moving vehicle, the sensor must allow a standoff distance of 6 to 12 inches, and have a measurement range of about 3 inches or more.

For rut depth measurement a similar range, resolution, and standoff distance is required, although lower sampling rates are sufficient because the rut depth is averaged over longer lengths.

Table B-1 presents a comparison of the performance capabilities of the sensors described above, along with some other important factors. The Infrared Sensor from Southwest Research is immediately available from FHWA for use in this system. Though its sensitivity to variations in surface reflectivity is of concern as an error source, the availability makes it a logical candidate for both profile and rut depth measurement with the system. The Selcom infrared sensor is a second, more promising alternative that appears to eliminate the reflectivity problem, although it comes at higher initial cost and still has a potential problem of signal dropout in holes and cracks. Inasmuch as Selcom units can be obtained on loan from the FAA at the time of test, they also make a logical choice for evaluation. At this point the K. J. Law optical sensors do not warrant consideration, both because they contain moving parts, and because of cost and licensing issues. The frequency limitations on the acoustic sensors disqualify them for profile

TABLE B-1 Non-contact Sensor Comparisons

Sensor	Initial Cost	Sampling Rate	Nominal Accuracy	Range	Comments
KJL/MDOT (Optical)	$20,000	750 Hz.	0.01 inch	6 inch	Moving parts License req'd
Southwest Research	$8000	500	0.1	3	FHWA owned
Selcom	$12000	16K	0.01	10	FAA loan avail.
KJL (Acoustic)	N/A	200	0.02	6	License req'd
Massa	$200	100	0.02	22	

measurement; however, they are candidates for rut depth measurement, and their low initial cost makes them attractive choices. Thus it is proposed that a Massa sensor be obtained and evaluated in the system for the rut depth measurement function.

Accelerometers

The second critical transducer in the measurement of the profile is the accelerometer used. The accelerations on the sprung mass of the profilometer vehicle are measured and then double integrated to obtain the vertical motions for the point of reference for the road following system. The integration process places critical demands on the accelerometer transducers. Thermal drift, resolution limits, and hysteresis result in offsets, which when double integrated cause erroneous indications of elevation. This problem is controlled in profilometers by passing the accelerometer output through a high pass filter to strip off low frequency drift. This process, however, causes the final profile to appear different from the true road because of the attenuated wavelengths, and the phase shift effects in filtering cause a different profile to be obtained when measured from opposite directions. Steps may be taken in the design of the system to minimize the possible compromises in the data acquired because of these problems. The most basic step is the direct recording of the accelerations and road follower signals, so that this compromise can be dealt with at the data reduction phase. Then, depending on the use of the data, an appropriate effort can be expended to minimize the consequences of filtering.

In calculation of quarter car statistics and waveband roughness parameters, the missing long wavelengths and phase shifts do not have any significant influence on the final result. However, in measuring profile for bituminous fill calculations or for later use in unknown ways (from the archival records) the consequences cannot be predicted. Thus, reduction with the best known methods is recommended, and the use of the best accelerometers is warranted.

The state-of-the-art in accelerometers appropriate to this application is identified in Table B-2 which provides comparative specifications for several accelerometers that are candidates for use in a profilometer system. In selection of an accelerometer it is important that the resonance properties be compatible with the filtering and sampling frequency to be used. Specifically, the accelerometer should not have a lightly damped natural frequency in close proximity to the folding frequency because of the aliasing that can result. For example, a resonant peak at 375 Hz combined with a sampling frequency of 400 Hz (200 Hz folding frequency) can potentially allow the resonance to appear as a 25 Hz acceleration in the output signal. Similarly, the overall combined effects of resolution, nonlinearity, and hysteresis are important properties impacting on the long wavelength reach of the accelerometer. Among those shown, the Sunstrand QA-900 provides the best price/performance ratio, and is a likely choice for the profilometer.

As the system will be configured, there will be provision in one of the operating modes for the raw accelerations to be measured and recorded directly as the most complete record of the

Table B-2 Specifications and Price of Selected Linear Servo Accelerometers

	Sundstrand OA-1200	Schaevitz LSB	Sundstrand OA-900
Range-Full Scale	±60g, ±12 Vdc max.	±0.25g to ±50g	±30g, ±12 Vdc max.
Output	1.3 ma/g nom. (1)	±5.0 volts	±1.3 ma/g nom. (1)
Natural Freq.	800 Hz min.	50 to 200 Hz (2)	500 Hz min.
Damping	0.3 to .7	0.3 to 1	0.3 to 0.8
Linearity	0.20 mg/g^2	0.05% of F.S.	0.03 mg/g^2
Threshold	0.001 mg	-	0.005 mg min.
Resolution	0.001 mg	0.0005% of F.S.	0.005 mg min.
Hysteresis	0.001% of F.S.	0.02% of F.S.	-
Repeatability	0.003% of F.S.	-	-
Composite Error	-	-	-
Cross-axis Sen.	2 mg/g max.	2 mg/g max.	2 mg/g max.
Bias	± 10 mg max.	±0.1% of F.S. max.	±10 mg max.
Bias T.C.	±0.135 mg/°C (3)	±0.002%/°C	±0.09 mg/°C nom.
Scale Factor T.C.	±0.018%/°C max.	±0.02%/°C	±0.018%/°C nom.
Shock	250 g, 11 ms (4)	100 g, 11 ms	250 g, 6 ms
Weight	2.3 oz	3 oz	2.3 oz
Price	$1775, $1860 (4)	$860	$990

(1) Current output. Range set by external resistor

(2) Dependent on g range

(3) As low as 0.01 mg/°C on special order

(4) 1000 g, 0.5 ms on special order

measurement. During reduction to a profile on the operating system, the acceleration signals can then be processed through a highpass digital filter in opposite directions during the integration steps to eliminate phase distortion.

Static Cross Slope Measurement

The third type of sensor of interest in profilometry is one which adds capability to measure static cross slope (and ultimately, the road grade). The vertical gyroscope is the state-of-the-art method for obtaining a vertical reference from which the measurement can be made. However, vertical gyroscopes of high accuracy which could provide an acceptable reference for periods up to an hour before the profilometer would have to be stopped for re-erection of the gyroscope, cost on the order of $20,000. Further, they are precision instruments that require trained operators for their use. Gyroscopes of a more reasonable cost (in the range of a few thousand dollars) have much higher drift rates, and would have to be re-erected every few minutes. At the other extreme, a simple pendulum can also provide a vertical reference. Yet the period of the pendulum must be selected large enough that it is not excited by normal steering actions in the vehicle, because the pendulum is unable to discriminate lateral accelerations of the vehicle from the gravitational acceleration to which it aligns. Normal straight ahead steering activity contains considerable content at 0.1 Hz and below. Further, curves in a road typically require as much as 30 to 60 seconds to negotiate. The pendulum period should be at least an order of magnitude greater, but a pendulum with a 600 second period (10 minutes) is difficult to build, and would be more difficult to erect than a gyroscope.

Another alternative, which is less expensive than a high precision gyroscope, is the combination of a lower priced yaw rate gyro with measurement of the transverse acceleration on the body of the vehicle. By this method the actual lateral acceleration can be computed (from the yaw rate times velocity) and subtracted from the acceleration measured on the transverse accelerometer leaving only the gravitational component indicative of the roll angle of the vehicle body. By subtracting the body roll angle relative to the road (measured by the road follower system), the cross slope of the road is obtained.

Although the complete development of hardware and methodology for measuring static cross slope with a profilometer is beyond the scope of this project, the availability of a high quality inertial reference system from FHWA (the Humphrey system), makes it possible to attempt implementation on this profilometer. The experience will further aid in assessing the feasibility of including specialized hardware, such as a vertical gyroscope, as a profilometer component.

Signal Conditioning System

In designing the profilometer a multi-channel signal conditioning system is called for because of the lack of the necessary signal conditioning functions in the computer hardware available. Most commonly, computer add-on boards begin at the level of analog-to-digital conversion. Yet before this stage, the signals must be brought to appropriate levels, DC components must be stripped off to avoid compromising the dynamic range of the digitization process, and anti-aliasing filtering must be applied. A signal conditioning system similar to that used in the UMTRI Data Acquisition system is seen as the best answer to that need. While it is not a normal commercially available component, it is a developed component and can be documented in the project such that it can be built by others.

Nine channels are needed for the measurement of two-track profiles, cross slope, and rut depth. In the UMTRI design each channel can provide the power source for the transducer to which it is connected, and each has a programmable gain that can be used to scale the output signal to the optimum level for the digitizer. In the case of the vertical accelerometers, significant bias offsets are called for to balance out the 1 g static acceleration present on those channels.

Because it is the last stage prior to digitization, the signal conditioner must provide anti-aliasing filters on each channel. The filtering frequencies must be tailored to the operating speed (because sampling is distance based), and must be optimized for the frequency content in each signal. The UMTRI design meets these needs by use of programmable filters that can be set by the computer as a part of its normal control function, thereby reducing the work load on the operator, and the chance for error in operation.

Additional features desirable in the signal conditioning system are that it lend itself to routine checking of its functional state, and to the calibration process. These features are included in the UMTRI design by incorporation of switching relays at the input stage of each channel, so that the computer can substitute its own signal for each transducer to confirm proper function, and to determine the gains and offsets for each channel. Though it would be desirable, there is no practical means by which the signal conditioner can be designed to allow direct calibration of each transducer. Nevertheless, with the proper computer routines it is possible to determine that the transducers are at a nominal condition at certain points in the profilometer operation.

Digitizing System

With the broad range of computer hardware available, it is practical to include the digitizing function within the computer using commercial components. At the suggested sampling interval of every 3 inches along the pavement, the digitizer must accommodate a 300 Hz sampling frequency on nine channels. At this rate, the time lag between sampling of each channel (slew) is not very important, but the designer should be aware of this phenomenon. In order to sample at pavement intervals the digitizer must provide means to accept the sampling command via an external signal. The available digitizing resolution normally falls into the 8 to 16 bit range. In this case, 12 bit resolution is appropriate, inasmuch as that equates to measurement resolution of 1 unit in 2048. With the road followers, for example, 1 bit would correspond to approximately 0.001 inches.

Computer System

Much is said elsewhere in this report with regard to the selection of the computer system and its peripherals. Appendix C in particular addresses the cost versus performance issues. At this point, it is only necessary to mention some of the broader considerations that the designer should keep in mind in the design of a profilometer. The computer is the heart of the system and should be selected as much for reliability, availability, and serviceability, as for performance. These types of considerations constitute a strong bias in favor of familiar systems like the IBM PC in applications like this because of the benefits in operator confidence and readily available service with use of the system. Though specialized laboratory computers, such as those available from Data General, Digital Equipment Corporation, and others are competent machines, selection of one of these less familiar (and normally more expensive) machines should only be made when advantages can be identified and evaluated.

An integral part of the computer decision, is the selection of peripherals. For the information acquired by the profilometer there is need for a large mass storage device to handle the many thousands of data values accumulated during a test. Magnetic tape storage is the most cost effective because of its relatively low price and high storage densities. Though nine track reel-to-reel tapes have been the standard in the past, the modern cassette systems are much smaller, more convenient, less expensive, and provide the recorded data on a much more portable medium.

For information output to the operator, both soft- and hard-copy systems are needed. The familiar CRT-type computer monitor is the natural and most versatile mode of soft-copy output by which the operator can communicate with the system and review data. The needs for hard-copy output include printing of alphanumeric information about test ID, system information, test results, etc., as well as perhaps even examining measurement traces of profile or rut depth. In the past this latter function has been provided by graphical recorders. However, with the development of dot matrix printers, both types of functions can be served by this one type of printer with associated savings in cost, the need for power in the profilometer, and a savings of interior space.

Though not essential to a profilometer, a data output means in the nature of the industry standard floppy disks is also recommended. This feature on a profilometer can add greatly to its versatility by providing a convenient and universal method for transporting data to other facilities. Though floppies are not an efficient method for handling the massive amounts of data acquired in the raw state, they are ideal for recording summary results and even individual profiles. By choosing a computer format compatible with most office information systems, reduced data can be transferred to the office environment.

APPENDIX C

Engineering Economics Analysis of Profilometer Configuration

The knowledge about the operative state of the road network is one of the main concerns of agencies responsible for managing, maintaining, and rehabilitating a network. This information is obtained by various means ranging from subjective and qualitative ratings to the use of sophisticated measuring equipment. The profilometer is an instrument which yields many figures of merit of the pavement condition and as such is a useful tool for the agencies responsible for the highways.

The profilometer considered in this research consists basically of a sensor system mounted on a vehicle which measures the distance to the pavement surface relative to an inertial reference system, and a computer system which acquires, stores, and/or processes the data.

There are many possible sensor systems and computing systems which can perform the functions of the profilometer. Costs associated with each differ as do the advantages and shortcomings of each configuration.

The objective of this appendix is to explore the engineering economics of the possible profilometer configurations. The analysis consists of:

1) Identification of the feasible equipment configurations to be considered.
2) Calculation of the annual capital and maintenance cost of each configuration.

3) Determination of the operating costs of each configuration for each of the program modes identified in Appendix A.

4) Determination of how effectively each configuration meets the performance requirements identified in Appendix A.

Many different types of sensors and computer systems were considered in the initial stages of this research. A set of three different noncontact sensors made it to the final consideration. Three different computer systems also made it to the final stage.

The sensor system in the profilometer could consist of three or five noncontact sensors, plus one or two accelerometers. The noncontact sensors considered are the Selcom laser sensor, the FHWA infrared sensor, and the Massa acoustic sensor. A sensor system could consist of all (3 or 5) Selcom or FHWA sensors. It could consist of 2 Massa sensors for rut depth, and either a Selcom or FHWA sensor for profile. It could also consist of 3 Massa and either two Selcom or two FHWA sensors. In each case, one accelerometer is also needed for each profile track. These eight combinations constitute a feasible and reasonable sensor system. An all Massa system was ruled out as inadequate for obtaining a good longitudinal profile and mixing the Selcom and FHWA systems was ruled out as inefficient. Table C-1 lists the costs assumed in this analysis for each of the sensor types.

The computer systems considered for the final choice were the Masscomp CCS-540 Data Acquisition and Computation System, the Data General 5/20 System and an IBM PC system. Table C-2 lists

Table C-1

Capital Cost of Profilometer Sensors

Sensor	Initial Cost per Sensor	Comments
SELCOM Laser	$12,000	Electronic box required with one or more sensors at a cost of $6000
FHWA Infrared	8,000	Cost is estimated. Further development of sensor is required
MASSA Ultrasonic	200	
Accelerometers	1,000	One required for each profile

Table C-2

Costs and Comparison of Attributes for a Profilometer Instrumentation System based on Three Different Computers

Computer System	Initial Cost	Data Acquisition	Computation	Flexibility	Service Availability
Data General	$35,000	slow-medium	slow-medium	good	poor
Masscomp	$49,000	fast	medium-fast	very good	poor
IBM PC	$19,000	slow-medium	slow-medium	good	very good

the initial costs assumed in the analysis for an instrumentation system (exclusive of sensors) based on each computer system. Also shown is a summary of their other relevant attributes.

Service Life and Maintenance Cost

One of the important assumptions in any engineering economic analysis of equipment is the service life. In this analysis it is assumed that the service life of the computer/instrumentation equipment is five years. This is an estimated lifetime generally used in the computer industry as the time before equipment becomes obsolete. After five years the equipment is still functional, but improvements in electronic technology have been such that faster, better, and cheaper equipment is usually on the market.

The annual maintenance costs in the industry are generally estimated as 10 to 15 percent of the initial cost of the equipment. Thus we will assume that the annual maintenance cost is 12% of the initial cost of the system. It will be assumed that at the end of the 5 years there is no salvage value for the equipment since it will be obsolete.

The sensing portion of the profilometer will consist of three noncontact sensors plus an accelerometer, or five noncontact sensors plus two accelerometers. There are eight feasible combinations of sensors for the system. If at least one Selcom sensor is used, an electronic box with an initial cost of $6000 is required.

The average service life of the sensors is not well documented. It is assumed here that a sensor will last at least five years unless the vehicle on which it is mounted is involved in an accident, or the sensor itself is hit by a rock. The second event is quite likely because the external mounting of the sensors leaves them quite vulnerable.

It is assumed that an annual maintenance cost of 20% of the initial cost should cover routine maintenance including replacement of broken sensors. It is expected that after five years, the FHWA and Selcom sensors could be reused and thus have a salvage value, estimated to be 50% of the original cost. The Massa sensors, and the accelerometers are assumed to have no salvage value after five years. Table C-3 gives the costs, service lives, and salvage values of all the possible components of the profilometer.

Calculation of Costs

The costs of each of the reasonable profilometer configurations are calculated by engineering economic methods. In this procedure the costs are computed using an interest rate. The interest rate chosen for the analysis is an annual rate of 10%. This value was selected to reflect the opportunity cost within a highway agency where the money could be used for some other project. It is also a value currently recommended for economic analysis of public investments (See Grant, Ireson, Leavenworth, "Principles of Engineering Economy", 6th Edition, Wiley, New York, 1976, p. 453). For sensitivity analysis the same annual costs were calculated with interest rates of 8% and 12%. The uniform annual capital and maintenance costs can be calculated from the

Table C-3

Costs, Service Life and Salvage Value of Components

Component	Capital Cost	Annual Maintenance Cost	Service Life	Salvage Value
SELCOM Laser	$12,000*	$2400	5 years	$6000
FHWA Infrared	8000	1600	5	4000
MASSA Acoustic	200	40	5	0
Accelerometers	1000	200	5	0
Data General Computer	35,000	7000	5	0
Masscomp Computer	49,000	9800	5	0
IBM PC Computer	19,000	3800	5	0

* An additional $6000 is required if one or more used

calculated from the following relationships:

Uniform Annual Capital and Maintenance Cost = Uniform Annual Computer System Cost + Uniform Annual Sensor System Cost

where

Uniform Annual Computer System Cost = Initial System Cost x (A/P,i%,5 yr) + Annual Maintenance Cost

Uniform Annual Sensor System Cost = Sum of Annual Costs for Each Sensor

Annual Cost for Each Sensor = Capital Cost x (A/P,i%,5 yr) + Annual Maintenance Cost - Salvage Value

The uniform annual capital and maintenance costs of the computer/instrumentation systems at interest rates of 8%, 10% and 12% are given in Table C-4. Similar costs for the different sensor types are given in Table C-5.

The annual cost for any possible combination of sensors and computer/instrumentation system can be calculated by adding the annual cost of the separate components. Table C-6 presents a matrix of annual costs for each of the eight possible combinations for an interest rate of 10%. Tables C-7 and C-8 show the same matrix for assumed interest rates of 8% and 12%, respectively. On comparing the tables, one notes that the difference between the annual costs for 8% and 12% only range from about $850 to $3500 depending on the system. Thus while there is a difference, the final costs are not very sensitive to the interest rate.

Table C-4

Uniform Annual Costs of Computer/Instrumentation Systems

	Assumed Interest Rate		
	8%	10%	12%
Data General	$15,764	$16,233	$16,709
Masscomp	22,070	22,726	23,393
IBM PC	8558	8812	9071

Table C-5

Uniform Annual Cost of Sensors

	Assumed Interest Rate		
	8%	10%	12%
SELCOM Laser	$4383	$4583	$4784
FHWA Infrared	2922	3055	3190
MASSA Acoustic	90	93	95
Accelerometers	365	382	399

Table C-6

Uniform Annual Cost of Profilometer at 10% Interest Rate

Sensors	Computer System Masscomp	Data General	IBM PC
3 FHWA (1)	$32,273	$25,780	$18,359
3 SELCOM (1)	38,440	31,947	24,526
1 FHWA (1) & 2 MASSA	26,349	19,856	12,435
1 SELCOM (1) & 2 MASSA	29,460	22,967	15,547
5 FHWA (2)	38,765	32,272	24,851
5 SELCOM (2)	47,988	41,495	34,074
2 FHWA (2) & 3 MASSA	29,879	23,386	15,965
2 SELCOM (2) & 3 MASSA	34,518	28,025	20,604

(1) - Cost includes one accelerometer
(2) - Cost includes two accelerometers

Table C-7

Uniform Annual Cost of Profilometer at 8% Interest Rate

Sensors	Computer System Masscomp	 Data General	 IBM PC
3 FHWA (1)	$31,201	$24,895	$17,689
3 SELCOM (1)	37,087	30,781	23,575
1 FHWA (1) & 2 MASSA	25,537	19,231	12,025
1 SELCOM (1) & 2 MASSA	28,501	22,195	14,989
5 FHWA (2)	37,410	31,104	23,898
5 SELCOM (2)	46,218	39,912	32,706
2 FHWA (2) & 3 MASSA	28,914	22,608	15,402
2 SELCOM (2) & 3 MASSA	33,339	27,033	19,827

(1) - Cost includes one accelerometer
(2) - Cost includes two accelerometers

Table C-8

Uniform Annual Cost of Profilometer at 12% Interest Rate

Sensors	Computer System Masscomp	Data General	IBM PC
3 FHWA (1)	$33,362	$26,678	$19,040
3 SELCOM (1)	39,808	33,124	25,486
1 FHWA (1) & 2 MASSA	27,127	20,488	12,850
1 SELCOM (1) & 2 MASSA	30,430	23,746	16,180
5 FHWA (2)	40,141	33,457	25,819
5 SELCOM (2)	49,775	42,992	35,453
2 FHWA (2) & 3 MASSA	30,856	24,172	16,534
2 SELCOM (2) & 3 MASSA	35,708	29,024	21,386

(1) - Cost includes one accelerometer
(2) - Cost includes two accelerometers

Estimation of Operating Costs

In this section the costs (excluding the annual costs) of operating a profilometer are explored. These costs are a function of the performance characteristics of the profilometer and also a function of how the profilometer is used. At this point the performance characteristics are not known with certainty. What follows is the best estimate for systems that have not yet been built. However, a reasonable amount of confidence accompanies these estimates. Profilometers can be used for a number of different missions described in Appendix A. The cost of operation will be looked at as the comparison of efforts expended to carry out these missions.

Labor - All the profilometer configurations considered could be operated by one person. However, for reasons such as safety, reliability, and common practice at highway departments, a two person crew will probably be used. Thus a two person crew is assumed for the analysis. The level of expertise necessary to run any of the 24 proposed combinations of equipment will be that of a technician. The training necessary to learn to operate the system should be about one week.

At this time it is assumed that all the proposed systems can be run at up to 55 MPH, so no extra labor costs for traffic control are required.

The 100% Survey - The best basis for comparing the 100% survey is the number of miles that can be surveyed in one day. The controlling factor here is the computer system. All profilometer configurations which have the Masscomp are assumed capable of acquiring data continuously for 150 miles. After 150 miles the tape must be changed. This is also a reasonable time for a driver break. If time for crew breaks and tape changes is included, these systems can acquire data for a 100% survey at the rate of 450 miles/day.

The Data General computer system can acquire data continuously for 50 to 60 miles before a tape change is necessary. At that interval, the vehicle would have to stop, go back for one mile, accelerate to measuring speed, and continue acquiring data. Assuming a continuous capability of 55 miles and including crew breaks means that in one day a crew can record data for about 375 miles.

The limits of the IBM PC in acquiring data continuously are not precisely established. In the best possible case it will be able to acquire data continuously for 50 to 60 miles at which time the tape must be changed. In this case the system will behave like the Data General system and will be able to survey 375 miles of road in one day. In the worst case, the IBM PC will be able to acquire data for only ten continuous miles. At that time a few seconds are needed to empty the storage buffers onto tape before more data can be acquired. In this case after every ten miles (taking a time of about 11 minutes) the vehicle must stop and back up, a maneuver which will take about four minutes. Thus 40 miles can be measured in one hour. Allowing for crew breaks, this means that 280 miles can be covered in one day.

Table C-9 shows the operating costs for the 100% survey of 1000 miles for a system based on the three computer systems. The

Table C-9

Comparison of Labor Cost to Conduct 100% Survey of 1000 Miles

System	No. of Days	Miles Driven	Total Cost*
Data General	2.66	1038	$740.00
Masscomp	2.22	1014	650.00
IBM PC (Best case)	2.66	1038	740.00
IBM PC (Worst case)	3.57	1200	975.00

* Costs are based on assumed rates of $90/day for a technician, and $.25/mile vehicle operating cost

Table C-10

Computer Time Estimates for Processing 1000 Miles of Raw Data into Quarter-Car and Rut Depth Statistics

	Computer System		
No. of Sensors	Data General	Masscomp	IBM PC
3	4.86 hours	4.86 hours	8.33 hours
5	11.1	11.1	16.66

time given in the table does not include the time required to process data. Table C-10 gives the computer times needed to process the raw data into quarter-car summaries and rut depth summary statistics. The computer is sensitive to the number of sensors in the profilometer; therefore, there are six possible combinations to be considered.

Other Operating Modes - There will be no difference among the systems in the time required to conduct a 50% sample survey. Similarly, no differences in operating times are indicated for the modes of identifying sections for maintenance, checking new construction, or in calibrating RTRRMS. It is difficult to make any statement about comparison of time for research purposes since research by its nature is not a standardized procedure. However, even here it is difficult to identify differences. The computer time necessary to process the raw data into just a profile is estimated to be the same for all three computer systems at 10 seconds/mile with three sensors, and at 20 seconds/mile with five sensors.

Cost Effectiveness

Comparing the cost effectiveness of different combinations of hardware, of course, is dependent on the utilization expected in the different missions of the profilometer. We may note that the difference in uniform annual costs between the most powerful and expensive computer system (the Masscomp) and the least expensive (the IBM) is generally on the order of $15,000 per year. The higher computational capacity, however, is only projected to have a real impact on operating efficiency in the 100% continuous survey mode. In that case the labor costs are nominally $775/1000 miles ($650 for survey plus $125 for data processing) for the Masscomp system and $1165/1000 miles ($975 plus $190) for the IBM, assuming worst case performance. The additional labor cost of $390/1000 miles with the IBM is balanced against the $15,000/year differential in uniform annual cost for the Masscomp system. Only in the case where the system is dedicated to 100% continuous survey work at the rate of 40,000 miles per year would any savings be possible by choosing the more expensive basic computer system.

Though the penalty in uniform annual costs with the Data General system is smaller ($7000 to $8000/year), the higher labor costs lead to a similar conclusion. Inasmuch as the IBM based system emerges as most cost effective, even with the worst case assumptions, it constitutes the rational choice for a system.