CHAPTER 2

ROAD SURFACE ROUGHNESS MEASUREMENT SYSTEMS

2.1 INTRODUCTION

The road roughness measuring device used in the PICR was the Mays-Ride-Meter manufactured by the Rainhart Company[1]. This instrument was modified by the Instrumentation Group with the replacement of both the graphical recording output unit and the mechanical odometer, the resulting unit being designated Maysmeter. This device measures the accumulated motion of the vehicle chassis relative to its rear axle, as the vehicle moves along a road surface. The number read by the instrument (in inches) divided by the distance travelled by the vehicle (in miles) is the inches/mile index for that road. This index was accepted as representative of the level of roughness present on the road.

The main advantages of the Maysmeter, like other response-type systems, are its relatively low cost, simplicity of operation, and high measuring speed. However, the measurements are influenced by the characteristics of the host-vehicle, by the type of pavement, and by environmental factors (Gillespie *et al.*). Stability over time, calibration and correlation with other similar and dissimilar systems are problems. It is thus essential to establish a method for correlating each Maysmeter's output with a road roughness standard. The General Motor's Road Surface Dynamics Profilometer was acquired to perform that function in the PICR and was employed to establish and to monitor the Maysmeter control sections used in the necessary calibration, all according to a methodology developed by members of the Research team (GEIPOT/PICR, Working Documents 5, 6, 7 and 10).

Recently Alckmin *et al.* questioned the validity of the roughness data collected with the Maysmeter for certain applications. Their work shows that the intrinsic limitations of the instrument (e.g. hysteresis and quantization), together with its acute and uncontrollable sensitivity to environmental and operational factors, as well as to the state of the host-vehicle, renders it unable to attain the minimum accuracy level required by some of the studies and experiments on the PICR. It also points out that the uses of the Maysmeter in the PICR are much more demanding than its applications in the U.S.A., where the instrument is virtually never used on unpaved roads.

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[1] The addresses for the manufacturers mentioned in the text appear in the reference section at the end of this work, in alphabetical order.

2.2 MAYSMETER

The Maysmeter is a road surface roughness recorder that is installed in a standard vehicle as shown in Figure 2.1. It was selected for use because of high data production capabilities, low cost, and demonstrated field reliability, based on its wide usage in the United States. Seven Maysmeters were used in the project. During their operation in a harsh environment, the devices themselves proved to be very durable.

The MRMs were supplied by the manufacturer with a pen and paper type graphical display unit (Figure 2.2). As the vehicle is driven over a road, the chart recorder displays a coarse road profile as it moves the paper at a rate proportional to the roughness of the road. Thus, the physical length of the strip of paper produced by the chart recorder is a measure of the roughness. A typical strip chart is shown in Figure 2.3.

Measuring the strip of paper to obtain roughness took approximately as much time as to generate it. In order to automate the data collection process while improving the reliability and productivity of the Maysmeter[2], the Instrumentation Group developed a summation unit which replaced the chart recorder. The summation unit accumulates the roughness information produced by the Standard Rainhart transmitter and displays it at selectable intervals in a digital form.

The roughness measuring device used in this study consists of three major parts (Figures 2.4 and 2.5). The transmitter installed is shown in Figure 2.6 and senses the motion of the vehicle chassis relative to its rear axle. It is part of the Mays-Ride-Meter manufactured by Rainhart Co.. The Distance Measuring Instrument (DMI) measures the distance travelled by the vehicle. It is manufactured by Nu-Metrics. The summation unit combines the distance information from the DMI and the chassis motion information from the transmitter and produces a summation display at specified distance intervals. It was manufactured by the Instrumentation Group and its construction details are given in a Project Instrumentation Memo (Linder, "Digital Readout for the Maysmeter"). More details about each of the three parts are given in an-

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[2] It was later verified that, in addition, the chart recorder's stepper motor is unable to perform adequately on rough roads.

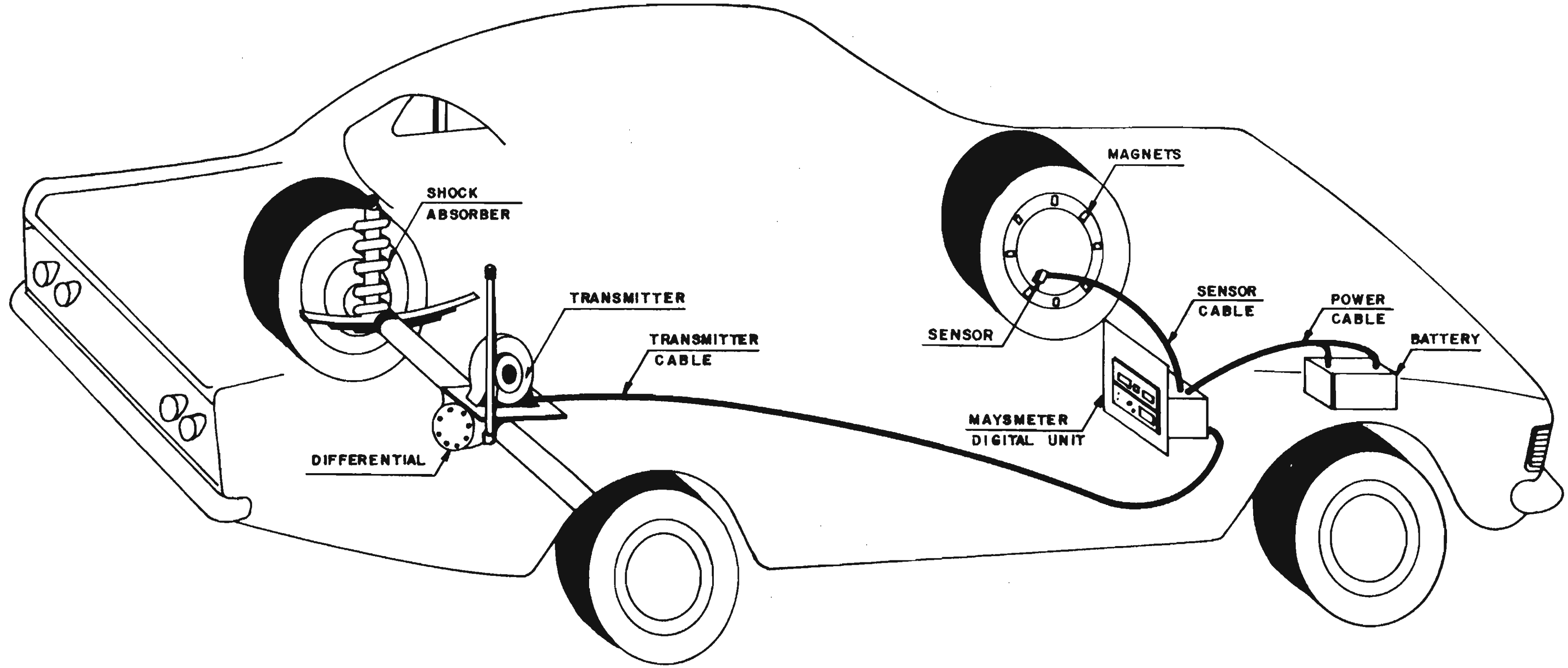

FIGURE 2.1 - MAYSMETER INSTALLED IN A CAR

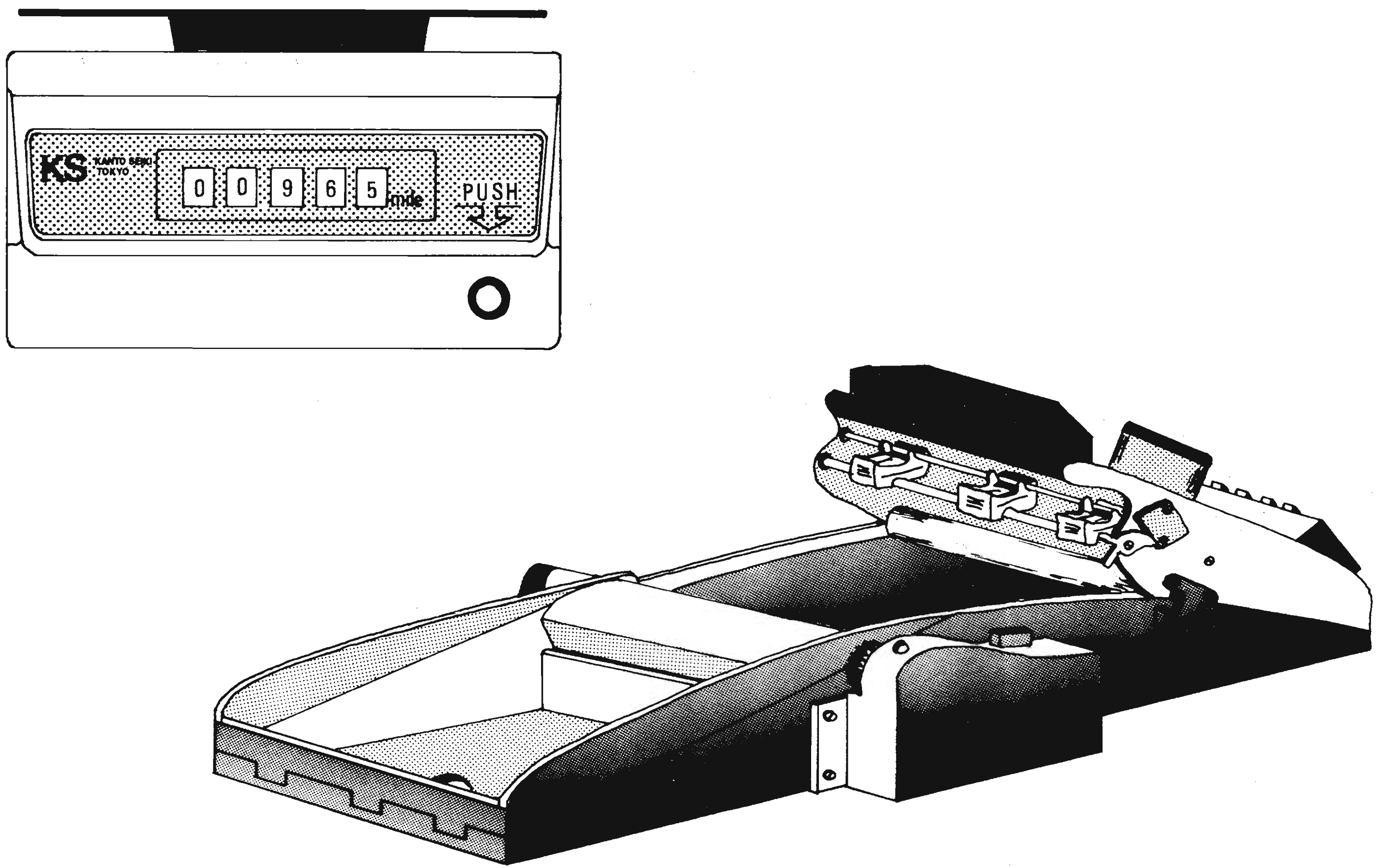

FIGURE 2.2 - GRAPHICAL RECORDER AND MECHANICAL ODOMETER

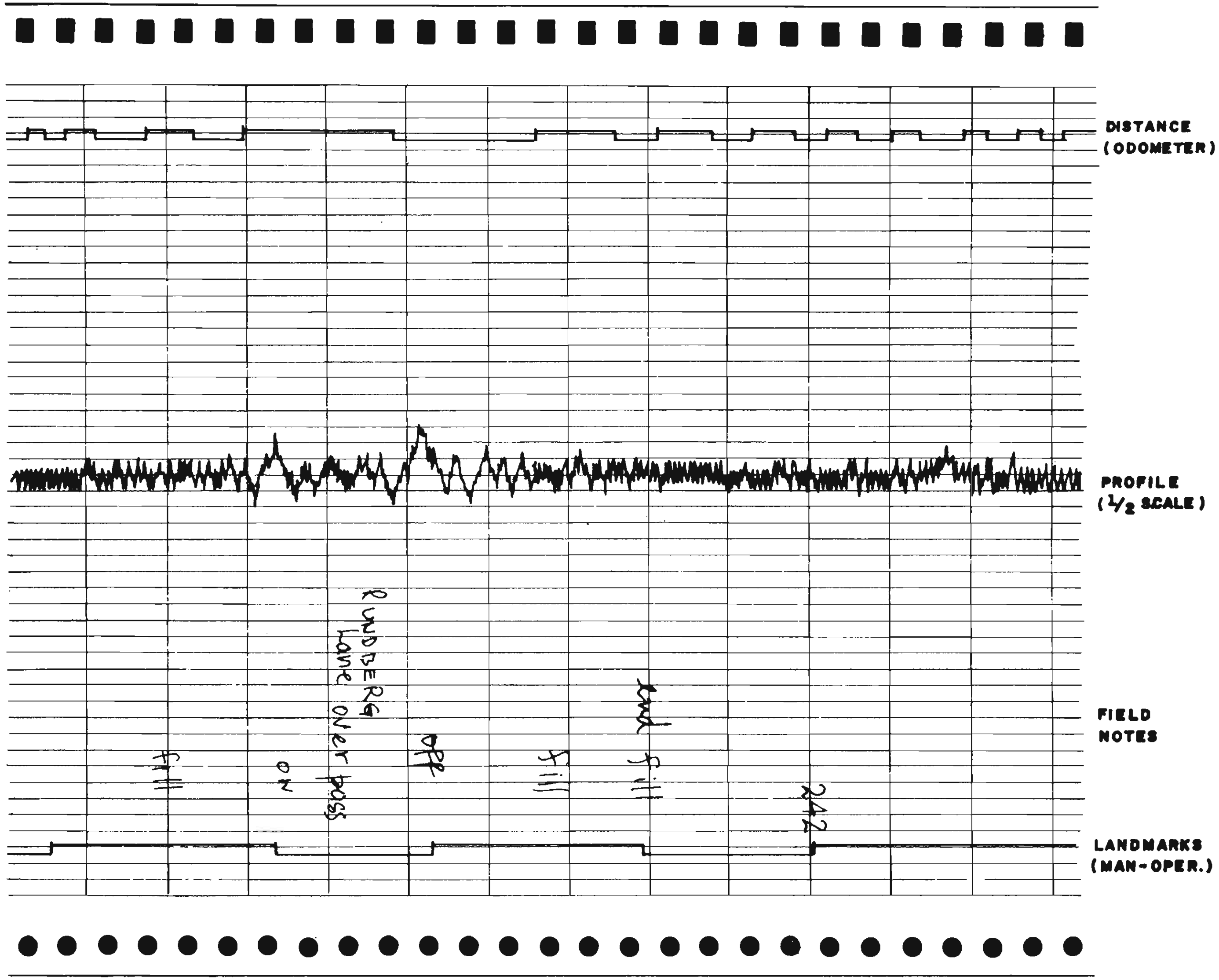

FIGURE 2.3 - GRAPHICAL MODEL CHART RECORDING

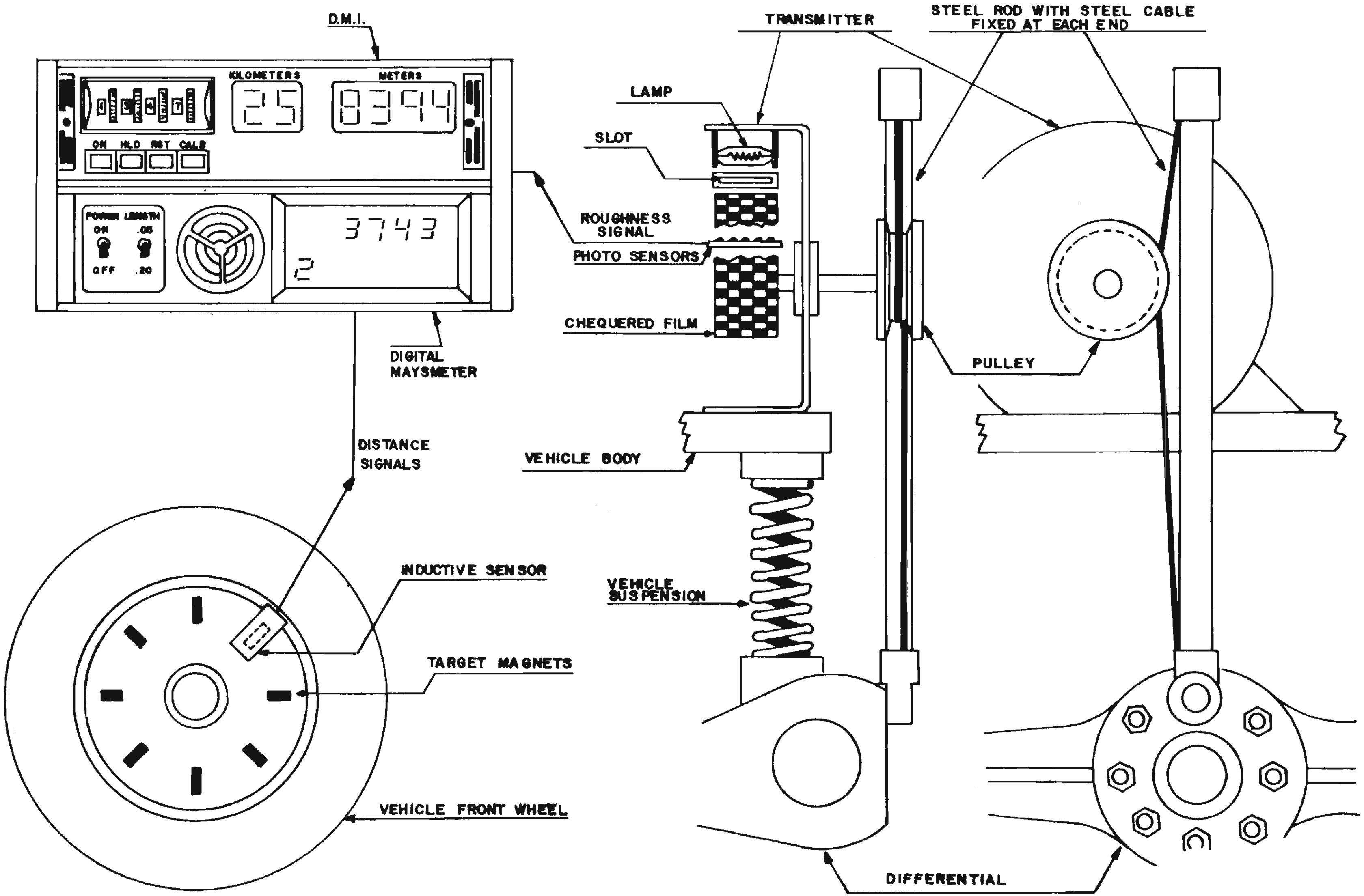

FIGURE 2.4 - MAYSMETER BLOCK DIAGRAM

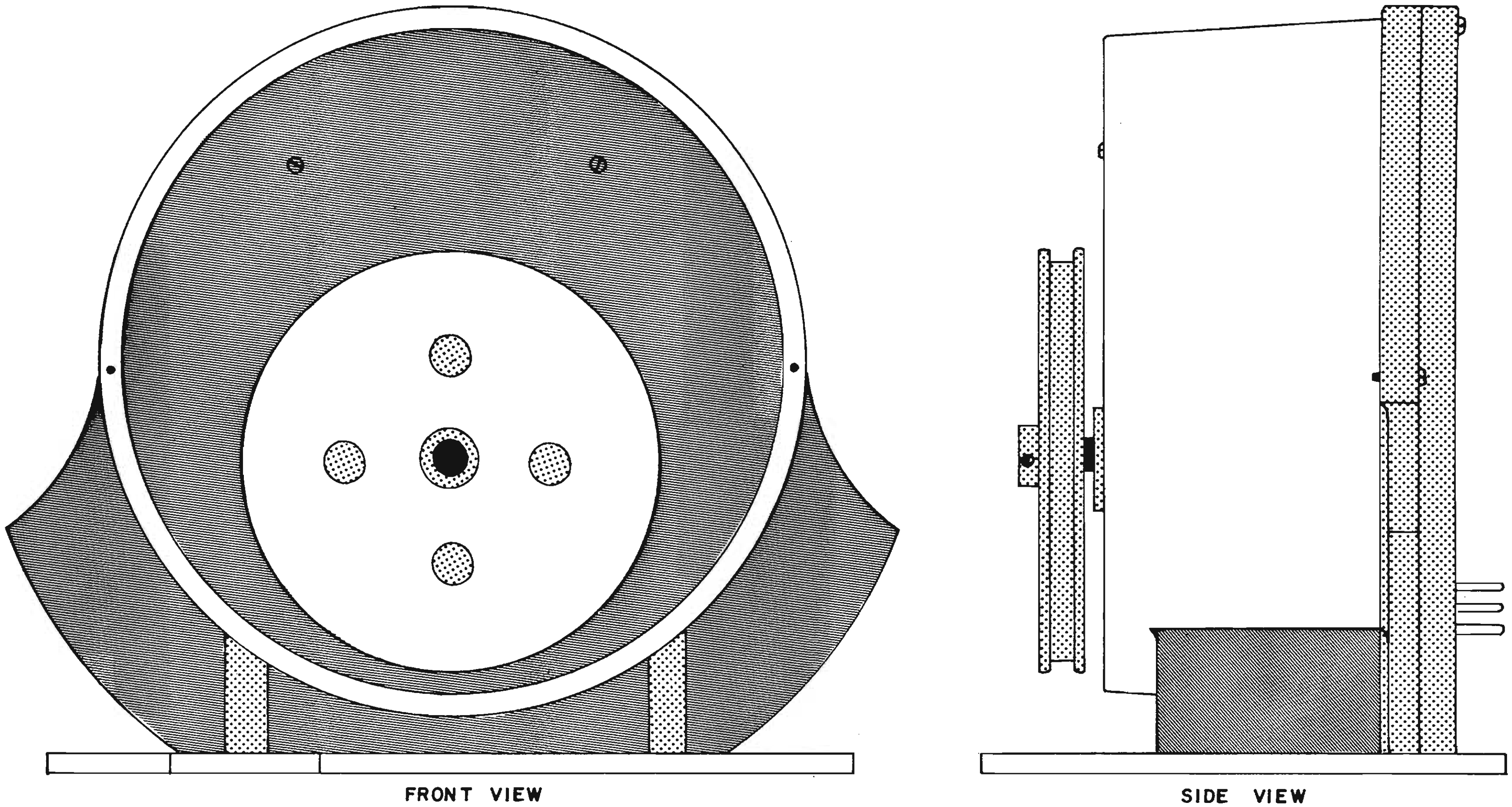

FIGURE 2.5 - TRANSMITTER

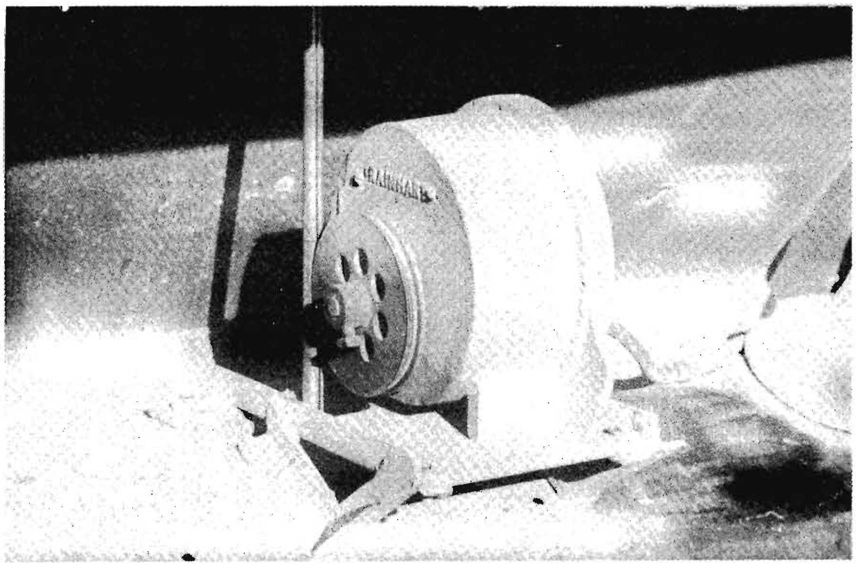

FIGURE 2.6 - MAYSMETER TRANSMITTER INSTALLED

TABLE 2.1 - SPECIFICATIONS FOR THE MAYSMETER SYSTEM

	DIGITAL OUTPUT	GRAPHICAL OUTPUT
MOUNTING		
Transmitter	Trunk	Trunk
Output Unit	Instrument Panel	Front Seat
Odometer	Instrument Panel	Instrument Panel
POWER	10 VDC to 14 VDC	10 VDC to 14 VDC
FREQ. RESPONSE (Roughness)	Limited by Response of Vehicle	Limited by Stepper Motor Response (200 Hz)
DIMENSIONS		
Transmitter	6.5"x7.5"x4.5"	6.5"x7.5"x4.5"
Output Unit	8.5"x 6"x 4"	11"x 18"x 8"
Odometer	Part of Output Unit	6"x 4"x 3"
SPEED	16 km/h to 80 km/h	Dependent on Roughness
OUTPUT DISPLAY	Digital Number Appearing on Instrument Face	Strip of Paper from Chart Recorder with length Proportional to Roughness

other Project Memo (Linder, "Digital Readout Mays-Ride-Meter System"). The resulting vehicle unit, whose specifications are summarized in Table 2.1, was designated the Maysmeter system and is referred to as the Maysmeter.

2.2.1 *Operating Principle*

The Maysmeter registers the relative change of position between the vehicle's rear axle housing and its chassis as the vehicle moves along a road surface. The rougher the road surface becomes, the greater the up and down motion of the chassis relative to the rear axle. The motion is sensed by the transmitter which is driven by a rod attached to the vehicle's rear axle housing. The transmitter sends electrical impulses to the summation unit. The summation unit is shown in Figure 2.7 and produces a numerical output, proportional to the motion between the rear axle housing and chassis.

The summation device uses an electronic distance measuring instrument (DMI) to measure the distance of each road subsection under study. The DMI senses the passage of 8 target magnets fixed to the inner rim of the vehicle's left front wheel, which are shown being installed in Figure 2.8. The DMI then scales the number of magnets sensed to produce an output display and signal which is proportional to an operator adjustable distance measurement unit, e.g., miles, feet, meters, etc.

The DMI may be read directly by the observer at the same time that it sends electrical pulses to the summation unit, which collects them until either 500 or 2000 (selectable by the observer) impulses are accumulated. The summation unit then updates its display to read out the accumulated roughness impulses from the transmitter. Since the DMI may be calibrated in any distance unit, the 2000 impulses may be 200 meters, 0.2 miles, or any other unit of measure (similarly, 500 impulses may be 0.05 km, 0.05 miles, etc.).

2.2.2 *Field Operation*

The Maysmeter is sensitive to operating speed, primarily because of the vehicle's spring shock absorbers system. Therefore, it is

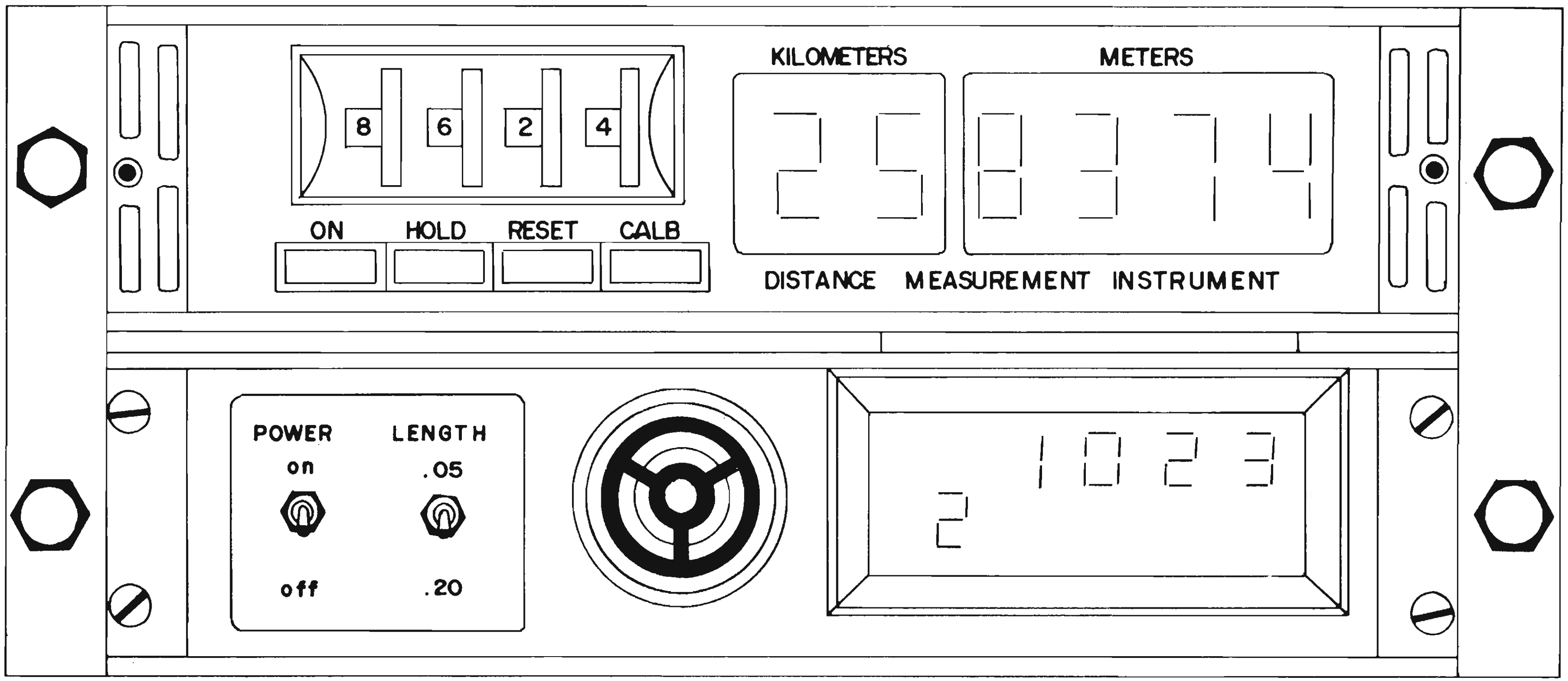

FIGURE 2.7 - DIGITAL ODOMETER (DMI) AND SUMMATION UNIT

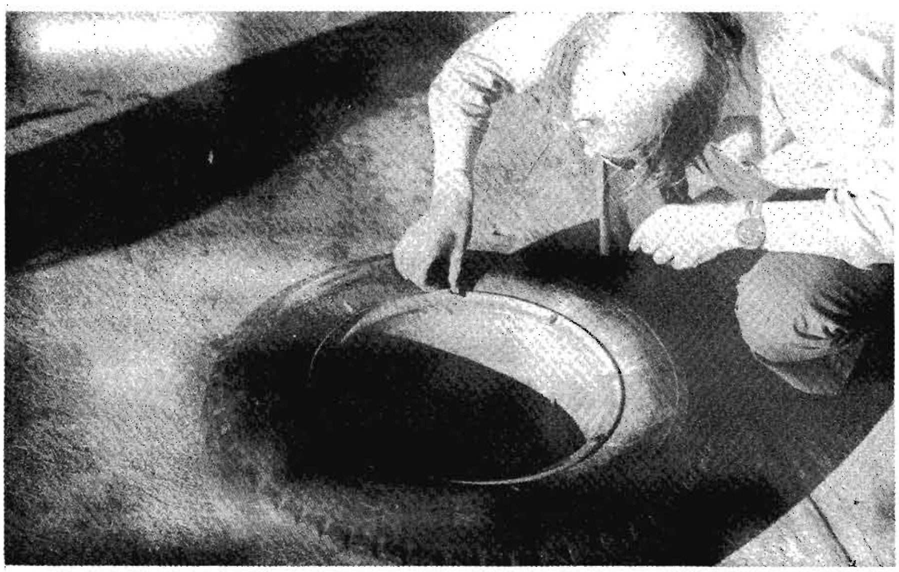

FIGURE 2.8 - INSTALLATION OF MAGNETS ON TIRE RIM

necessary to establish standard fixed speeds for measurements. For the study three operating speeds were established, 20 km/h, 50 km/h, or 80 km/h, depending on the type of road. Correlation equations were developed to convert 20 and 50 km/h speed roughness results to 80 km/h values. These equations are presented on GEIPOT/PICR, Working Document No. 10, 1979. The validity of these equations for pavements other than asphaltic concrete is questioned by Alckmin *et al.*

The Maysmeter required a driver and an observer. The driver was carefully selected and trained to drive at a constant speed and not to swerve or turn abruptly, as such behavior introduces false data into the measurement device. The observer required very little training, but had to be able to assume overall responsibility for the crew and equipment. He instructed the driver to drive at a preselected standard speed appropriate to the road surface being measured. The observer also operated the Maysmeter device and recorded roughness information on the recording form, shown in Table 2.2.

The summation model is operated as follows: the observer holds the DMI reset switch in until the start of the section and jots down the roughness count for each sub-section on the recording form, along with identifying information. The recording forms are returned to the office upon the vehicle's return.

A normal operating schedule includes the following:

- Before the crew sets out with the Maysmeter for the measurement site, the vehicle and instruments are checked for defects.
- The Maysmeter is tested on established calibration sections.
- Once the Maysmeter arrives at its measurement site, it is again tested on previously established control sections in the area.
- During extended measurement programs in remote areas the Maysmeter is periodically checked against control sections established during the measurement program to continuously verify calibration.
- Following the completion of any Maysmeter measurement program and upon return to the Instrument Shop the unit is again checked on the headquarters calibration sections.

The headquarters control sections were monitored for change using the GM Profilometer, described in Section 2.3.

2.2.3 Maintenance

Some introductory comments are in order regarding the envi-

MT - GEIPOT

PICR - ESTUDOS DOS PAVIMENTOS

OPERADORES
X = 1 INTERVALO DO MM = 320 m
X = 2 INTERVALO DO MM = 80m
Y = Nº DE INTERVALOS DO MM POR SUB-TRECHO

IRREGULARIDADES COM MAYSMETER

C	RODOVIA	TRECHO Nº	DATA D D M M A A	VEÍCULO Nº	X	Y	VEL.	SEN-TIDO	PERC.
7 6									1
7 6									1
7 6									2
7 6									2
									3
									3
6									
7 6									1
7 6									1
7 6									2
7 6									2
7 6									3
7 6									3
1 2	3 4 5 6 7	8 9 10	11 12 13 14 15 16	17 18 19 20	21	22	23 24	25 26	27

LEITURA DE IRREGULARIDADE								
1a.	2a.	3a.	4a.	5a.	6a.	7a.	8a.	9a.
28 29 30 31	32 33 34 35	36 37 38 39	40 41 42 43	44 45 46 47	48 49 50 51	52 53 54 55	56 57 58 59	60 61 62 63

TABLE 2.2 - MAYSMETER ROUGHNESS DATA RECORDING FORM

ronmental conditions in which the equipment was operated. Heavy summer rains caused unpaved roads to become slippery and muddy. In winter, the lack of moisture cause these same roads to become covered with a powdery dust which seeped through every small crack in the vehicle and equipment. The severity of road surface roughness caused fractures in the chassis of three Maysmeter vehicles. Several types of mechanical failure occurred on the seven vehicles, including collapsed suspension, broken motor mounts, torn-off exhaust systems, cut tires and bent wheel rims, dented fuel tanks, and general body damage.

Tires lasted about 20,000 kilometers and it was difficult to find sufficiently round ones for replacement. The normal procedure was to select each tire individually from the dealer's stock to ensure that the best ones available were being used on the Maysmeter vehicles.

2.2.4 *Recommended Maintenance Facilities*

One electronics technician
One auto mechanic
Volt-Ohm meter
Oscilloscope (15MHZ) optional
Normal electronic hand tools
Normal mechanical tools

2.2.5 *Major Sources of Maintenance Problems*

Little is known about how the graphical model Mays-Ride-Meter functions in the Brazilian environment because its use was discontinued very early in the project. Some problems were encountered, however, on very rough surfaces with the paper drive system of the chart recorder. The paper lost contact with the drive sprockets, causing an inaccurate roughness measurement.

The most recurrent problem was breakage of the transmitter bow-rod drive cable. The drive cable is a flexible steel cable similar to a bicycle hand brake cable. Although strong, it is susceptible to wear from friction. Fortunately, it was easy to replace and readily available in Brazil.

Other problem involved loose bolts and screws, caused by vertical vibration on very rough surfaces. Operator preventive maintenance, which might have abated this problem, could never be adequately established.

The DMI sensor and target magnets were vulnerable to damage from flying stones or debris on unpaved roads. Sensors and magnets were also damaged by careless tire changes at local tire shops. The DMI Instrument failed on some vehicles due to environmental conditions, but more frequently it had electrical component failures. Three failures of the summation unit occurred from manufacturing defects.

The transmitter axle bearings were replaced on some units and the aluminum outer pulley was replaced with locally-made brass pulleys to increase their life span. The aluminum bow-rod and aluminum rod-to-cable clamp were replaced with stainless steel parts. Some problems were encountered with the transmitter photo cells, requiring the replacement of two units. The transmitter lamp needed to be replaced about once every six months due to heavy (daily) use.

2.3 PROFILOMETER

2.3.1 *Introduction*

The General Motors road surface dynamics Profilometer (Figure 2.9), manufactured under licence by K. J. Law Engineers Inc., was acquired to provide a reliable standard against which the Maysmeter results could be compared, to facilitate correlation among the seven Maysmeters. The Profilometer was thus used to establish and to monitor periodically the control sections used in the calibration of the Maysmeters. The correlation technique between Profilometer and Maysmeter was based on Walker and Hudson (1973).

The Profilometer experienced an abnormally high failure rate during most of the project. Important technical limitations of the instrument were found which restricted its use to smooth asphaltic concrete roads (GEIPOT/PICR, Working Document No. 10, 1979). Details are given in Section 2.3.4 on maintenance.

FIGURE 2.9 - PROFILOMETER IN OPERATION ON A TEST SECTION

2.3.2 *Operating Principle*

The Profilometer is a specially modified instrumented vehicle which, when driven over a highway, measures the road profile. Figure 2.10 illustrates the operating principle. The vehicle undercarriage has been modified to accept two spring-loaded pavement-follower-wheels. One wheel follows the right wheel path and the other the left wheel path. A linear potentiometer is connected between each follower-wheel axle and vehicle body to measure the distance between body and roadway. Two accelerometers are secured directly over the follower-wheels to sense the vertical motion of the body. The potentiometer and accelerometer signals are then electronically combined by the profile computer to cancel the body bounce and calculate the true road profile. The electrical representation of the road profile is registered continuously on a precision analog recorder for later analysis.

The Profilometer is also equipped with a Quarter-Car-Simulator. This is a special purpose analog computer designed to be used to process road profile data measured by the Profilometer. The processing of road profile data involves the analog simulation of a simplified vehicle. The measured road profile data is the input to this simulation. The reaction of the simulated vehicle to the measured road profile is the output. This output is in terms of the Roughness Index (RI) instituted by the Bureau of Public Roads, U.S.A..

The Profilometer is also equipped with a two-channel strip chart recorder. This graphic recorder is used to register the profile computer outputs during the calibration process.

The processing and recording instruments of the Profilometer are illustrated in Figures 2.11 and 2.12. The specifications of the Profilometer are summarized in Table 2.3.

2.3.3 *Field Operation*

The Profilometer was operated at 16 km/h on very rough surfaces and at 32 km/h on normal paved surfaces. Although, according to the manufacturer, the Profilometer may be operated at any speed, practice showed that there are important speed limitations that, if ignored, will lead to inaccurate operation and to equipment damage (GEIPOT/PICR, Working Document No. 10, 1979).

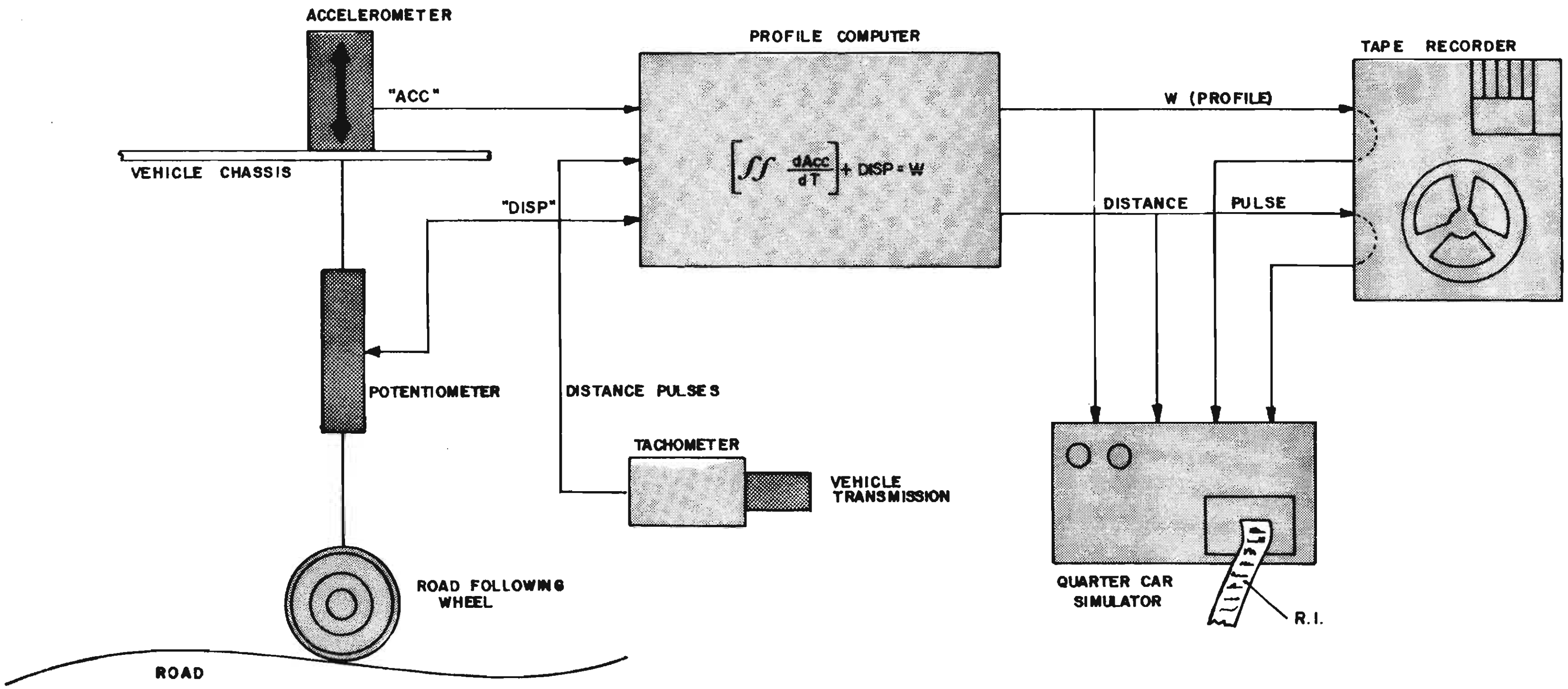

FIGURE 2.10 - PROFILOMETER BLOCK DIAGRAM

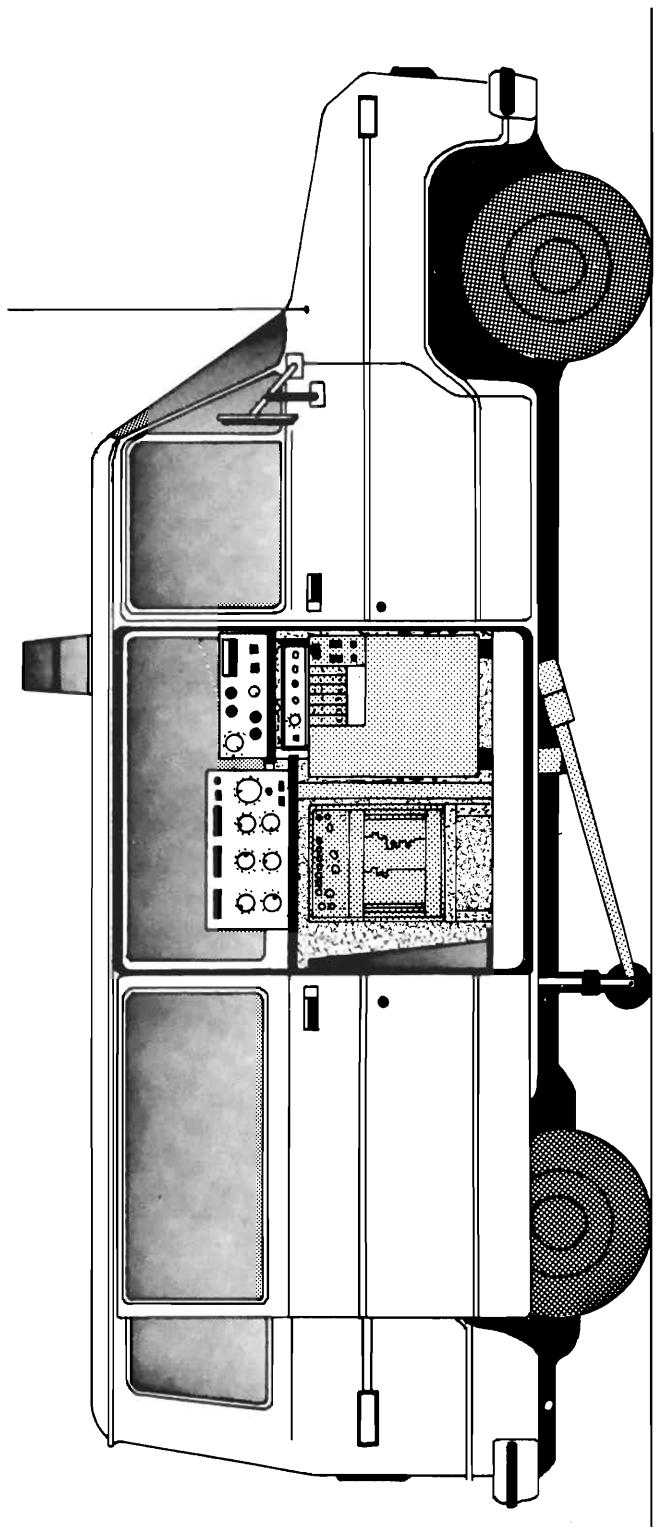

FIGURE 2.11 - PROFILOMETER

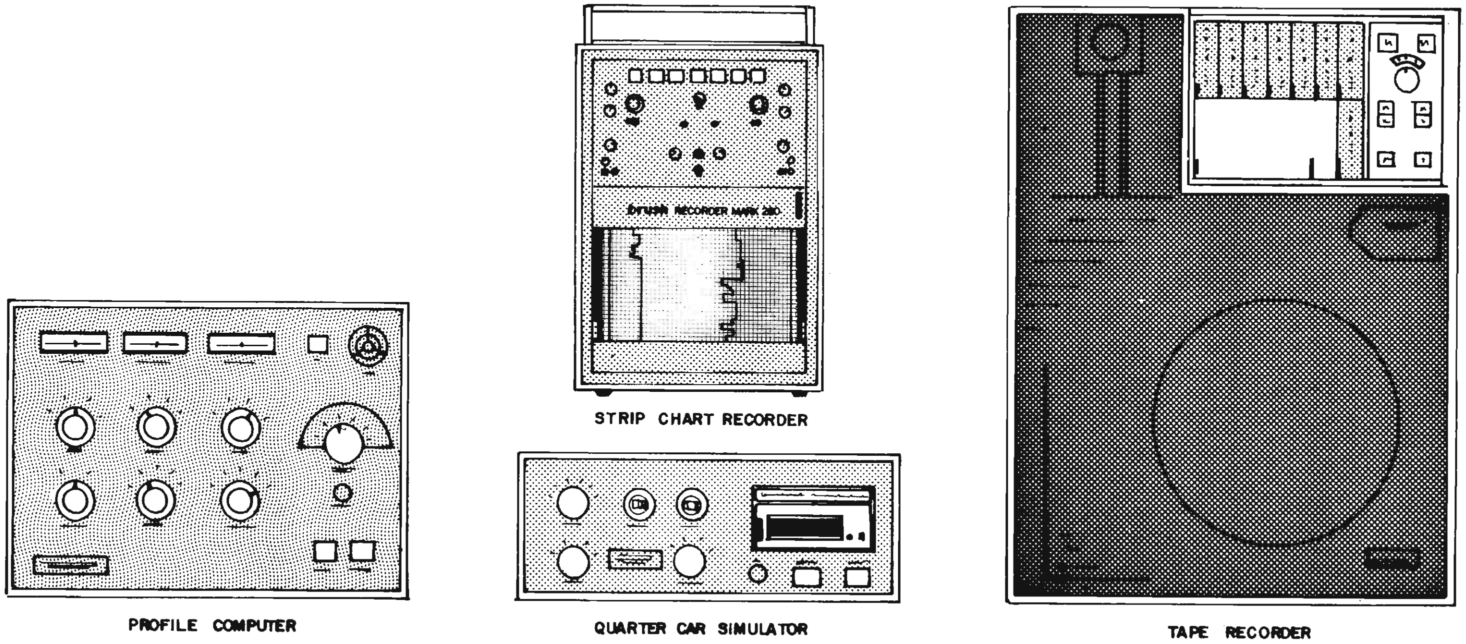

FIGURE 2.12 - PROFILOMETER PROCESSING AND RECORDING INSTRUMENTS

TABLE 2.3 - SPECIFICATIONS FOR THE PROFILOMETER

MOUNTING	All Profilometer components are installed in a medium weight Ford panel truck
POWER	Power self generated by alternators mounted on vehicle's engine
ROUGHNESS RESPONSE	Selectable by filter and gain setting and operating speed
SPEED	10 MPH to 50 MPH[1]
REPEATABILITY	± 1%[2]
OUTPUT	Profile recorded on analog tape RI index printed on paper

NOTES: [1] Standard speed should be established to assure best results. Higher speeds feasible only on very good roads.

[2] Chiefly dependent on the skill of the drivers.

The Profilometer's crew consisted of a driver and an operator. Accurate driving is critical since many road surfaces exhibit considerable transverse roughness gradients, and if the measuring equipment (Profilometer, Mays-Ride-Meter, etc.) is not driven over exactly the same wheel paths, repeat roughness measurements will vary for the same road. Thus, it is normal on patched roads to get a larger spread in repeat measurements than on very smooth roads. This is not so much a function of the measuring device's repeatability as a function of driver's repeatability. Therefore, the driver must be selected and trained with care if good results are to be obtained.

The operator had to be a mature individual, capable of making judgements as to the safe usage of the Profilometer on a particular surface, especially if the surface was in poor condition. The studies were to include unpaved and badly deteriorated paved roads. After many breakdowns had occurred, it was established that the Profilometer was not to be used if there was a possibility of damaging the measuring device. Later, the use of the Profilometer was restricted to smooth asphaltic concrete roads after it was found that this was the only type of road where the measurements were accurate, besides being safe. The operator instructed the driver and operated the computers and the tape recorder. The operator required substantial training before he was able to recognize Profilometer malfunctions and gain the experience necessary to enable him to correctly choose the gain and filter settings needed to achieve the best possible results from the Profilometer.

The operating procedures followed for the Profilometer were as follows: the Profilometer was stopped on the road, 200 to 300 meters in front of a measurement section of known length. The Profilometer's road-following-wheels were lowered, the profile computer reset and the operator entered verbal identifying information on the tape recorder. The driver started a gentle acceleration to the operating speed using the 200 to 300 meter stretch for that purpose. The operator entered the "start of section" signal on the tape recorder via voice or an event switch. As the Profilometer passed the end of the section, the operator entered the "end of section" signal to the tape recorder in the same way and raised the road-following wheels. When the Quarter-Car-Simulator was used, its printed tape output was annotated to reflect identifying information. Both the tape recording of the profile and the Quarter-Car-Simulator tape were returned to the office for analysis.

2.3.4 *Maintenance*

The Profilometer experienced an abnormally high rate of failure during most of the project's duration. Early in the project there were numerous electronic component failures in both the profile computer and Quarter-Car-Simulator. Some design and manufacturing errors were found in the circuit boards and corrected. Many components were replaced, and then the failure rate decreased considerably. This allowed the Profilometer to go to the field, revealing a major problem: potentiometer breakage. The potentiometer is the sensor that registers the change in position between the road-following wheel and the vehicle's chassis. Although the original potentiometers chosen by the Profilometer manufacturer were also used on large aircraft to sense the landing gear position, they failed to be durable enough for the Profilometer. Two original and four spare potentiometers were broken, repaired and broken again. The problem was solved only after a new pair of potentiometers was built by a potentiometer manufacturer especially for the project Profilometer, and with the reduction of the operating speed.

The change in the Profilometer operating speed revealed a design problem in the Quarter-Car-Simulator: the RI index was sensitive to the collection speed as well as to the simulation speed. The manufacturer was contacted and admitted that there was an error in one of the circuit boards. A diagram showing the changes to be made in the QCS circuit board was sent by the manufacturer but correcting factors were adopted instead, the circuit being left as it was (GEIPOT/PICR, Working Document No. 10, p.5, 1979).

Two accelerometers failed because of excessive Profilometer vibration. These failures occurred early in the project and the replacement accelerometers gave no problems.

An unusual failure occurred involving the torsion bars which hold the road following wheels to the road surface. Both torsion bars broke. The Profilometer manufacturer contacted the Chrysler Corporation Engineering Department and learned that if the torsion bars were allowed to remain wet they would break at an accelerated rate compared to normal. New bars were installed with a heavy coating of grease. No further torsion bar failures occurred.

The electrical system of the Profilometer was supplied by two alternators and battery sets. Each received a very heavy demand. Each failed on occasion, but this problem was considered normal and one that could be expected to recur.

The hydraulic system used in raising and lowering the road following wheels developed leakage from time to time. This was considered normal in view of the very high hydraulic pressure and the heavy usage of the Profilometer. A gas-charge booster tank developed a pin hole and was repaired by soldering.

The graphic recorder Brush Mark 280 (Clevite Corporation), used in the profile computer calibrations, presented increasing problems and was finally taken out of the Profilometer when it was no longer possible to repair it locally. This was an obsolete model graphic recorder built with technology from the late 50's. To replace it a UV graphic recorder was borrowed from the soils laboratory whenever it was necessary.

The Sangamo Sabre II tape recorder used in the Profilometer had electrical component failures which were a major source of Profilometer downtime from the middle of the project on. The recording and reproducing heads wore out extremely fast with use. The manufacturer was contacted and recommended changing the tape type. The record/reproduce heads were changed (approx. cost US$4.000) and the type of tape recommended was adopted. However, the new heads wore out as fast as the original ones. It was learned later that the recorder supplied with the Profilometer turned out to be one manufactured by Sangamo during a period of experimentation. Once this information was discovered, the recorder was shipped back to the factory and repaired at the manufacturer's expense. Even after the repairs, the recorder failed to give acceptable service. This recorder is not considered sufficiently robust for service in the Profilometer.

2.3.5 *Recommended Maintenance Facilities*

One electronics engineer
One senior electronics technician
One mechanic
Digital volt-ohm meter, 3 1/2 digits
Oscilloscope
Function generator, 1 HZ to 10KHZ
Frequency counter
Normal electronic hand tools
Normal mechanical hand tools