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W. D. Cunagin, S.O. Majdi and H.Y Yeom

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16. Abstract

Truck weight data are required for pavement and bridge design, truck size and weight enforcement, and the development of administrative policy and legislation. The efficient collection and analysis of these data require that truck weighing-in-motion (WIM) equipment be used. Lower cost WIM systems are necessary for use in meeting the needs of national and state agencies.

Several technologies have been investigated and used for lower cost WIM systems. Inexpensive, accurate, and reliable traffic sensors for weighing trucks, and detecting the presence of vehicles, as well as their axles, have been shown to be useful in previous research. One of these piezoelectric (piezo) cable, was investigated in a research effort jointly sponsored by the State of Iowa and Minnesota and Federal Highway Administration (FHWA) and in other work in the State of Washington and several European countries. A new piezo technology, which uses piezo film rather than the ceramic powder form employed in the piezo cable, was used in this study.

This study was conducted to evaluate piezo film WIM sensor technologies, produce an electronic data collection unit, and integrate the different assemblies with appropriate software to produce a low cost piezoelectric film WIM system. This work has been successfully completed.

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DEVELOPMENT OF LOW COST PIEZOELECTRIC FILM WIM SYSTEM

by

Wiley D. Cunagin

Saïd O. Majdi

and

Heon Y. Yeom

Research Report 1220-1F
Research Study 2-10-88-1220
Development of Low Cost Piezoelectric Film WIM System

Sponsored by

Texas Department of Transportation

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

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

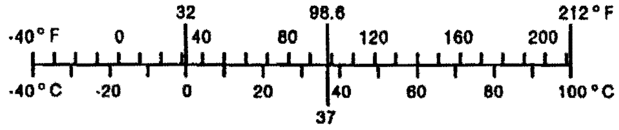
Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



ACKNOWLEDGMENT

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IMPLEMENTATION

This report describes the development of a low cost weigh-in-motion (WIM) system based on piezoelectric film technology. The availability of the design documentation for this device will enable the Department to procure additional units. These can be deployed in the State to acquire truck weight data on a wider basis than has been possible previously.

DISCLAIMER

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CHAPTER 1. INTRODUCTION

Truck weight data are required for pavement and bridge design, truck size and weight enforcement, and the development of administrative policy and legislation. The efficient collection and analysis of these data require that truck weighing-in-motion (WIM) equipment be used. However, the historically high cost of these devices has inhibited their deployment. Lower cost WIM systems are necessary if the needs of national and state agencies are to be met within the limited funding available for this purpose.

Several technologies have been investigated and used for lower cost WIM systems. These utilize piezoelectric (piezo) cable, piezo/carbon composite, capacitive strip, fiber optic, triboelectric, conductive rubber, and piezo film devices as WIM transducers. In most cases, the first effort with each lower cost sensor technology was the fabrication of axle sensors that could be used in automated vehicle classification (AVC).

Of the technologies listed above, piezo cable has received the greatest amount of attention recently. It was first investigated in this country in a research effort jointly sponsored by the States of Iowa and Minnesota and Federal Highway Administration (FHWA). Other work efforts were carried out in the State of Washington and several European countries. Piezo Cable is now being deployed on a limited scale.

A system based on capacitive strips has been developed by the Golden River Company in cooperation with academic researchers in the United Kingdom. That company is now trying to establish the technology. The technology was also addressed in a project funded by the Strategic Highway Research Program (SHRP) Ideas Deserving Exploratory Analysis program.

With the exception of piezo film, none of the other potential lower cost WIM technologies have been deployed other than under laboratory conditions.

This study undertook the development of a low cost WIM system based on piezo film technology. This has been accomplished through completion of a series of tasks carried out to evaluate piezo film WIM sensor technologies, produce an electronic data collection unit, and integrate these hardware assemblies with appropriate software to produce a low cost piezoelectric film WIM system. The following paragraphs include descriptions of the tasks as proposed.

TASK DESCRIPTIONS

The following task descriptions are quoted from the original study proposal agreement.

Task 1: Development of Piezoelectric Film Weighmat

The prototype piezo film weighmat has been tested under laboratory conditions. It appears to be very promising. However, the vendor (Pennwalt) needs to make some additional modifications to improve the accuracy, reliability, and durability of this device before it can be deployed on the highway. Under this task, TTI will work with Pennwalt to improve the design and construction of its WIM sensor, including its tire pressure measurement capabilities. The resulting sensor will then be tested in the laboratory and on the highway under actual traffic conditions. The laboratory and field data will then be analyzed to develop recommendations as to the applicability of this device to the Department's traffic monitoring activities.

Task 2: Evaluation of Piezoelectric Strip WIM Sensors

Laboratory testing of the piezo strip axle sensors produced by Pennwalt for testing under **Study 2038** gave results that indicate that they could be used as WIM sensors. That is, the output response was approximately linear over the range of simulated wheel weights from 1,000 to 10,000 pounds. Since piezo cable WIM sensors have received a great deal of interest recently, it would be worthwhile to evaluate the piezo film strip sensor as a WIM device. One advantage of this device is that it costs about one-third of what the piezo cable does. This will allow placement of multiple sensors, thereby allowing more samples to be obtained for the oscillating tires. This should allow signal processing techniques to be used that significantly improve the accuracy of the weighing operation.

Task 3: Final Report

TTI will prepare a final report describing the methodology and results of the research and making recommendations as to the feasibility of using each of the selected low cost WIM alternatives.

OBJECTIVE OF STUDY

The objective of this study was to develop one or more WIM systems, including both weight sensors and associated electronics, based on piezo film technology.

REPORT ORGANIZATION

Chapter 2 presents a brief overview of piezo film technology. Chapter 3 describes the work conducted and results obtained in the effort under Task 1 to evaluate the piezo film weighmat. Chapter 4 contains similar information regarding the piezo strip WIM sensors. Chapter 5 contains the study conclusions and recommendations.

CHAPTER 2. PIEZOELECTRIC FILM TECHNOLOGY

Piezo film is a flexible, lightweight, tough plastic film that has significant advantages as a sensor technology in other applications. These advantages have been generally recognized to include:

1. Wide frequency range - approximately 0 to 10^9 hertz (Hz).
2. Wide dynamic range - sensitive to both very small (10^{-8} or microtor) to very large (10^6 psi or Mbar) forces.
3. Low acoustic impedance - resulting in the ability to match impedance to that of water, human tissue, and adhesive systems.
4. High elastic compliance - giving the ability to faithfully reproduce input forces.
5. High voltage output - ten times greater than piezo ceramic for the same force input.
6. High dielectric strength - ability to withstand strong electrical fields (75 V/m) where most piezo ceramics fail.
7. High mechanical strength and impact resistance (10^9-10^{10} Pascal modulus).
8. High stability - resistant to moisture, most chemicals, oxidants, and intense ultraviolet radiation (0.01% water absorption).
9. Relatively low raw material and fabrication costs, particularly in volume quantities.

Additional properties are described in a later section of this chapter. First, a brief history of the development of piezoelectric materials and a discussion of the structure of piezoelectric film are presented.

BACKGROUND

The term "piezoelectricity" was derived from the Greek for "pressure electricity." It refers to the ability of some materials to convert mechanical energy into electrical energy.

Piezoelectric effects were first observed more than 100 years ago by Jacques and Pierre Curie. They discovered that quartz crystals produce an electrical charge when deformed. They also found that the crystals change in dimension when placed in an electric field. One of the first applications of this technology was made by Langevin when he built a quartz transmitter and receiver for underwater sound that evolved into the first "SONAR." Later efforts by researchers at the Massachusetts Institute of Technology (MIT) discovered that certain ceramics could be polarized to produce a high piezo response. Current SONAR systems still use ceramic-based transducers (1).

Research in the 1960's addressed piezoelectric effects in organic materials. One of the interesting findings in that effort was that human tissue and bone are piezoelectric. In fact, there is evidence that the sense of touch is derived from an electric charge created by the skin and transferred by the nervous system to the brain. It is therefore not surprising that piezo materials are being used as tactile sensors for industrial robots. One of the organic materials included in this research was a polymer known as polyvinylidene fluoride (PVDF). Kawai (2) discovered that polarized PVDF developed much higher levels of piezo activity than any other synthetic or natural polymer.

Piezoelectricity was defined in 1949 as "electric polarization produced by mechanical strain in certain crystals, the polarization being proportional to the amount of strain and changing sign with it." This definition also applies to piezo film (3).

PVDF STRUCTURE & MANUFACTURE

Chemically, PVDF is a long chain semicrystalline polymer of the repeat unit (CH_2-CF_2). Units of the monomer, vinylidene fluoride CH_2=CF_2, polymerize in an orderly fashion to give greater than 90% head-to-tail configuration: -CH_2-CF_2-CH_2-CF_2-. For this reason, the polymer exhibits the very high net dipole moment of its monomer constituent: approximately 7.56×10^{30} C-m (1).

The piezo properties of PVDF depend on its crystalline structure. There are three common phases for the material which are designated as alpha, beta, and gamma. The alpha phase is most common. It is non-polar and results when the melted PVDF resin is cooled. The beta phase forms after deformation of the alpha crystallites. For example, stretching PVDF film at temperatures below its melting point causes a packing of unit cells in parallel planes to give the polar beta phase. The gamma phase has an intermediate level of polarity between the alpha and beta phases. Mechanical deformation of the gamma phase polymer also yields beta phase crystallites.

Piezo film is created by "poling" the beta phase of the PVDF polymer. This process exposes the polymer to a high electric field at elevated temperatures. The level of piezoelectric activity depends on: (1) field strength; (2) poling time; and (3) temperature. The poling process produces a permanent orientation of molecular within the polymer.

When an external force is applied to the film results in compressive or tensile strain, the film develops a proportional open circuit voltage. A reciprocating force produces a corresponding, alternating electrical signal. The frequency response is very wide: from 0.005 Hz to gigahertz. The film also has a low Q. The half wave thickness resonance of 29 micrometer piezo film is approximately 40 MHz.

PIEZO FILM PROPERTIES

In addition to the properties presented at the beginning of this chapter, piezo film has several other advantages that make it an attractive choice for use in transducers. First, it is easily fabricated into unusual designs. Second, it can be cut, formed, and glued with commercial adhesives. Third, a variety of conductive electrode coatings and lead attachments are available.

Piezo film does have certain disadvantages that make it inappropriate for certain applications. Since it has a low Q, it is not a very good electromechanical transmitter, particularly at resonance and in low frequency applications. It does, however, make an excellent high frequency transmitter. In addition, the film has a maximum operating temperature of 100 °C. Also, exposed electrodes are sensitive to electromagnetic radiation. Good shielding techniques are required.

Piezo materials are anisotropic. That is, their electrical and mechanical responses differ depending on the axis of applied electrical field or axis of mechanical stress or strain. Piezo film can be annealed to provide temperature stability.

CHAPTER 3. DEVELOPMENT OF PIEZOELECTRIC FILM WEIGHMAT

The piezo film weighmat is intended to function in the same manner as is the capacitive weighmat that is now used by the Department for its portable WIM systems. It is expected to replace the capacitive weighmat when fully developed.

There are several reasons for this expectation. First, the piezo film material is extremely tough in commercial applications. A form of the piezo film material is used as a protective lining for tanks holding caustic chemicals. It has been used to monitor strain in helicopter blades - the blades failed before the piezo film did. It has been used in space to measure the impacts of micrometers under (obviously) very cold conditions. Second, the signal level produced by the piezo film transducer is at least an order of magnitude greater than other WIM transducers. As a result, the signal to noise ratio is also at least an order of magnitude higher, making readings more accurate and less in need of signal processing techniques.

Another expected advantage of the piezo weighmat is cost. Capacitive weighmats cost approximately $6,000 each. The projected price of the piezo weighmat is $800. The capacitive weighmat is also very heavy (about 80 pounds), while the piezo weighmat is approximately 20 pounds. The lower weight makes it easier to transport and deploy the piezo weighmat; its flexibility also assists in this effort.

The capacitive weighmat is susceptible to damage from parts dragged behind vehicles. The piezo weighmat is designed to resist most damage of this type. Finally, the durability of the capacitive weighmat has been questioned. The piezo weighmat has been developed to overcome this difficulty.

WEIGHMAT DESIGNS

Several different designs for the prototype piezo film weighmat were developed in conjunction with engineering staff of the vendor, the Pennwalt Corporation. These are shown in Figures 1 through 4. The weighmat shown in Figure 1 has a strip of active material that acquires a weight signal, while the rectangles are used to indicate the location of the tire on the transducer so that any nonuniformity in the piezo film can be compensated in the data collection software.

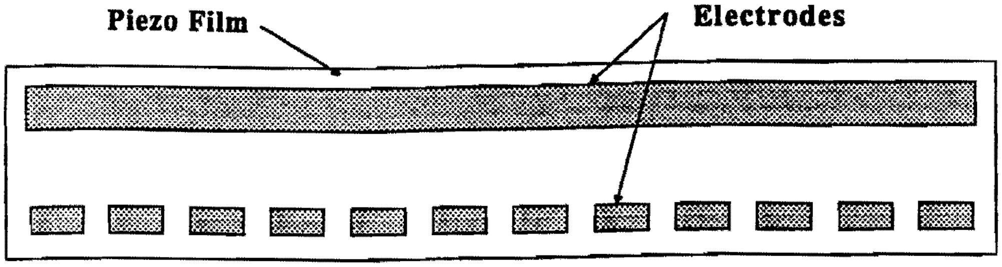

Figure 1. Weighmat Configuration I.

Weighmat Configuration II (see Figure 2) adds vertical sensor areas for more precise tire location and tire contact area for contact tire pressure measurement.

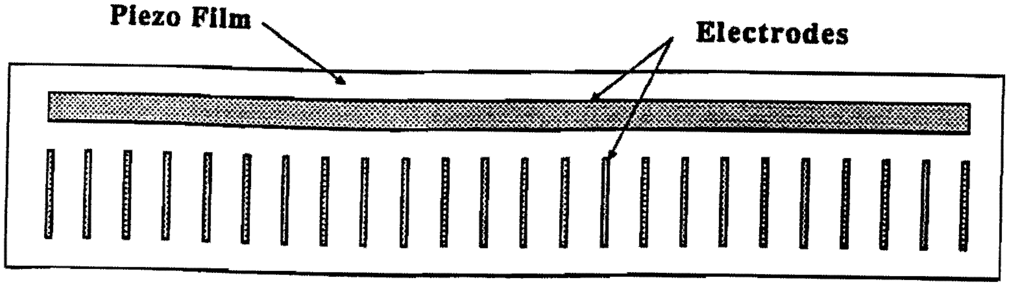

Figure 2. Weighmat Configuration II.

Weighmat Configuration III uses two sheets of strips, one horizontal and one vertical, to acquire more accurate tire contact area and tire contact pressure measurement as well as the weight signal.

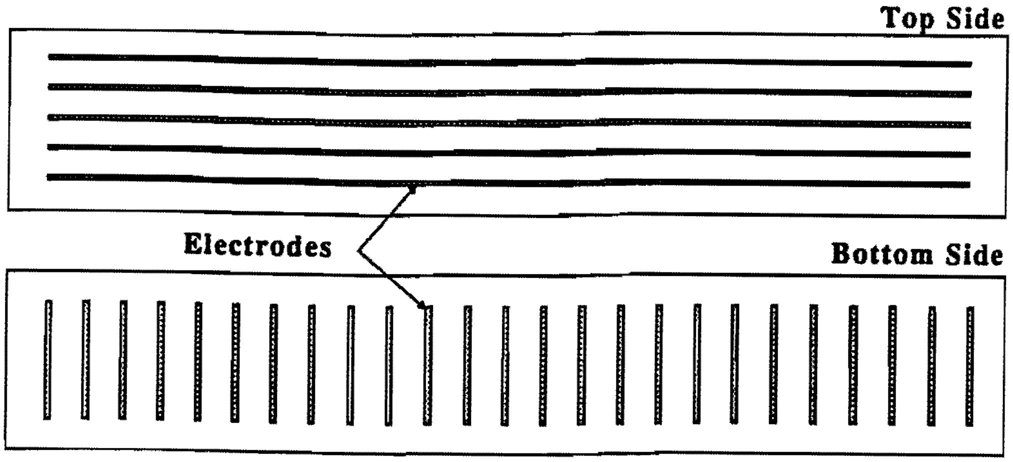

Figure 3. Weighmat Configuration III.

Weighmat Configuration IV is designed to have the entire tire on the sensor area at the same time. It is intended to be used in conjunction with an array of axle sensors that measure tire contact area.

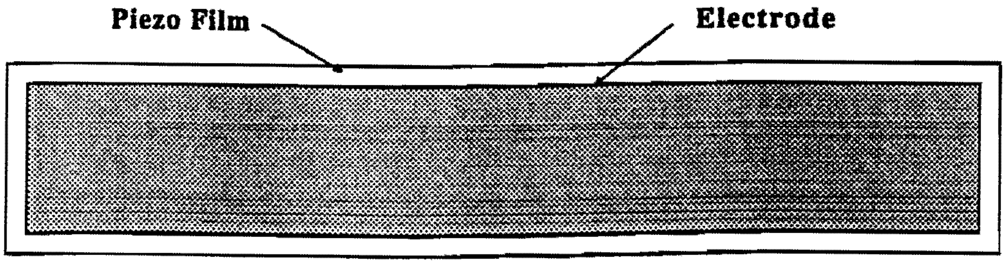

Figure 4. Weighmat Configuration IV.

Testing of the four piezo weighmats resulted in the conclusion that Weighmat Configuration IV, in conjunction with two axle sensors, one of which is placed diagonally, is the preferred device for use in this project. There are several reasons for this conclusion. First, Configurations I through III require between thirteen (Configuration I) and thirty (Configuration III) lead wires from the sensing area to the electronics at the roadside. These lead wires and their points of connection are potential areas of fatigue failure. Configuration IV uses only two lead wires thereby minimizing the vulnerability of the transducer to damage.

The second reason for selecting Configuration IV is that the continuous measurement of lateral tire placement provided by the diagonal axle sensor is more accurate than the discrete sensing points used in Configurations I through III. This is because knowledge of the exact position of the tire on the sensor aids in interpreting the signals produced by the transducer. In this way, known variability in the transducer can be accounted for in the system software.

The third reason for selecting Configuration IV is that the signal amplitude is an order of magnitude greater than that produced by any of the three other configurations.

The electronic system described in the next chapter was also used with the piezo weighmat.

CHAPTER 4. EVALUATION OF PIEZOELECTRIC STRIP WIM SENSORS

Whereas the development of the piezo weighmat described in the previous chapter is intended for portable use, both portable and permanent formats were used with the piezo strip sensors. Piezo axle sensors were obtained in two configurations. The cross section for the portable version of the piezo strip is shown in Figure 5. The cross section for the permanent version is given in Figure 6.

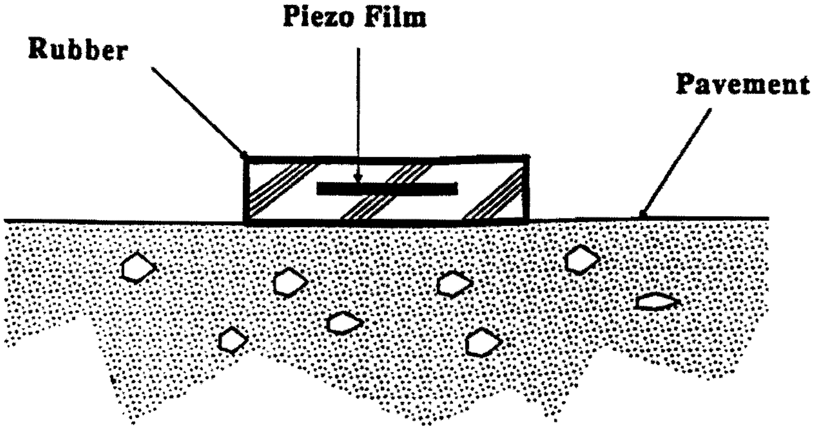

Figure 5. Cross section of portable piezo strip WIM sensor.

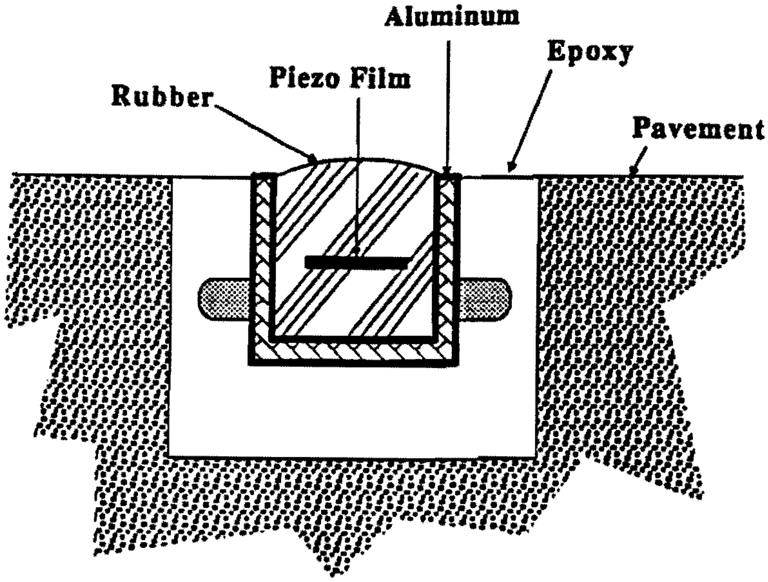

Figure 6. Cross section for permanent piezo strip WIM sensor.

The permanent piezo strip configuration has been used extensively by TxDOT in its implementation of AVC sites. Post-installation monitoring of these sites has indicated some damage of the sensors due to mechanical and water-related damage. In these cases, sensor failure has been due to damage to the urethane encapsulation structure and to the conductor leads rather than the film itself. Corrective measures have been taken to reduce these problems through improved sensor design and revised installation practices.

Laboratory and field tests of both types of piezo strip WIM sensor were carried out and are described in the following paragraphs.

LABORATORY TESTING

Laboratory testing for the piezo axle sensors consisted of applying loads to both piezo axle sensor configurations. The loads were applied at each of six test points located along each of the two sensors. The loads were varied from 1,000 to 10,000 pounds in 1,000 pound increments. They were applied using a Materials Testing System (MTS) through a platen in the shape of a truck tire footprint.

Figure 7 contains all of the laboratory test data for the temporary axle sensor. Each plot is for the loading level indicated in the key to the right of the figure. The same data are shown in three dimensions in Figure 8. The linearity of the response at each of the testing points is shown in Figure 9.

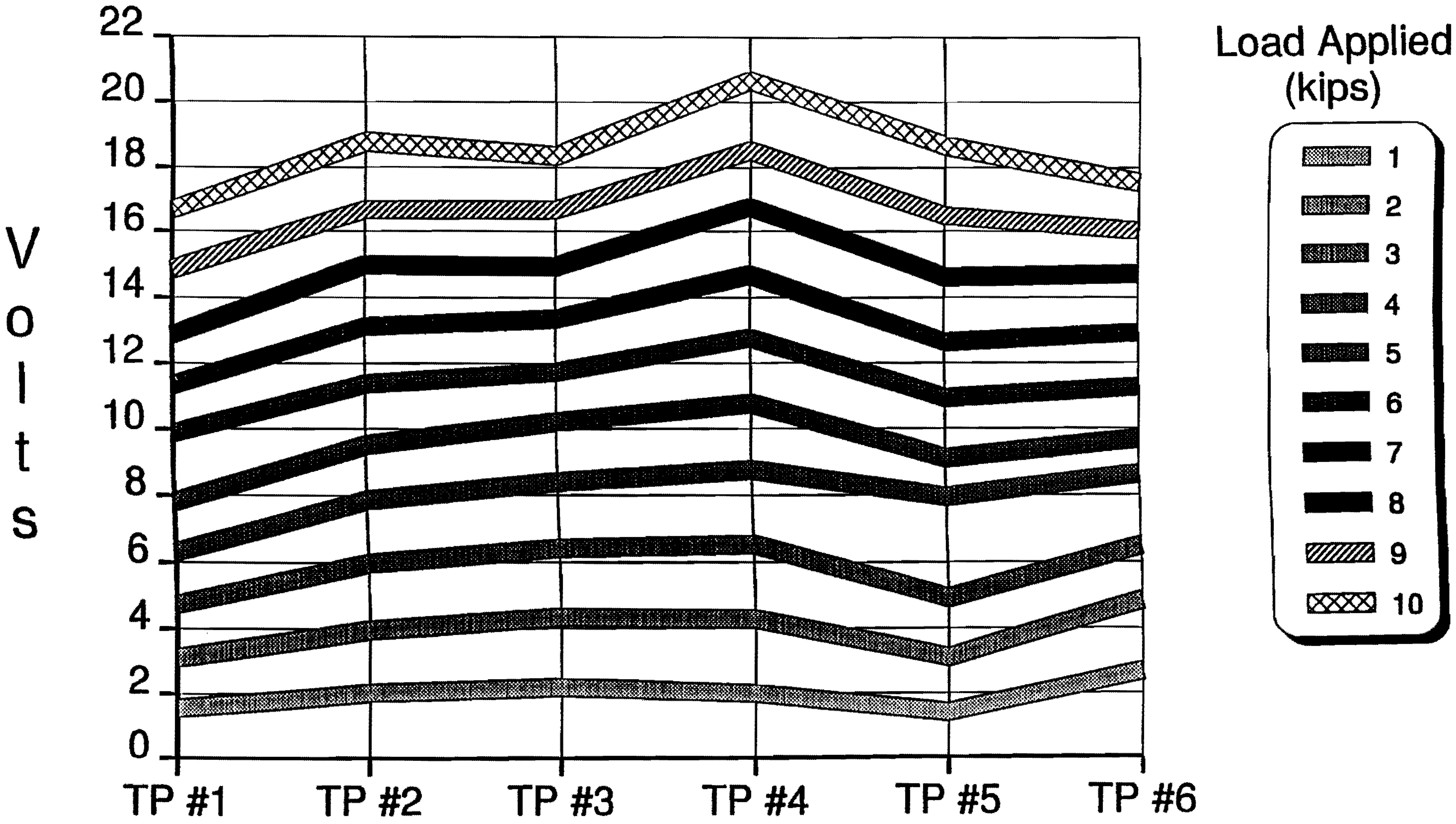

Figure 7. Response Profile of Temporary Piezo Strip Axle Sensor

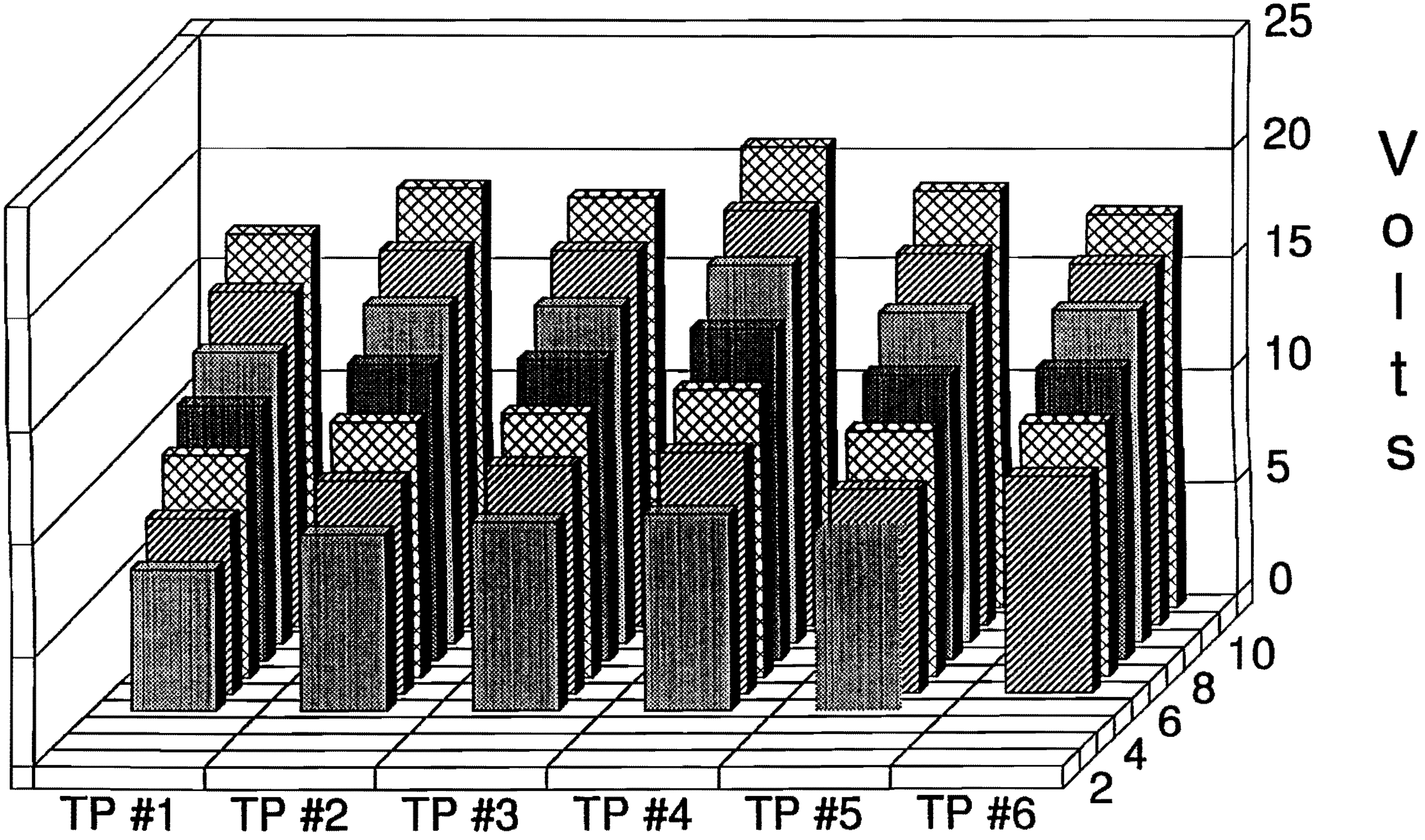

Figure 8. MTS Load Test of Temporary Piezo Strip Axle Sensor

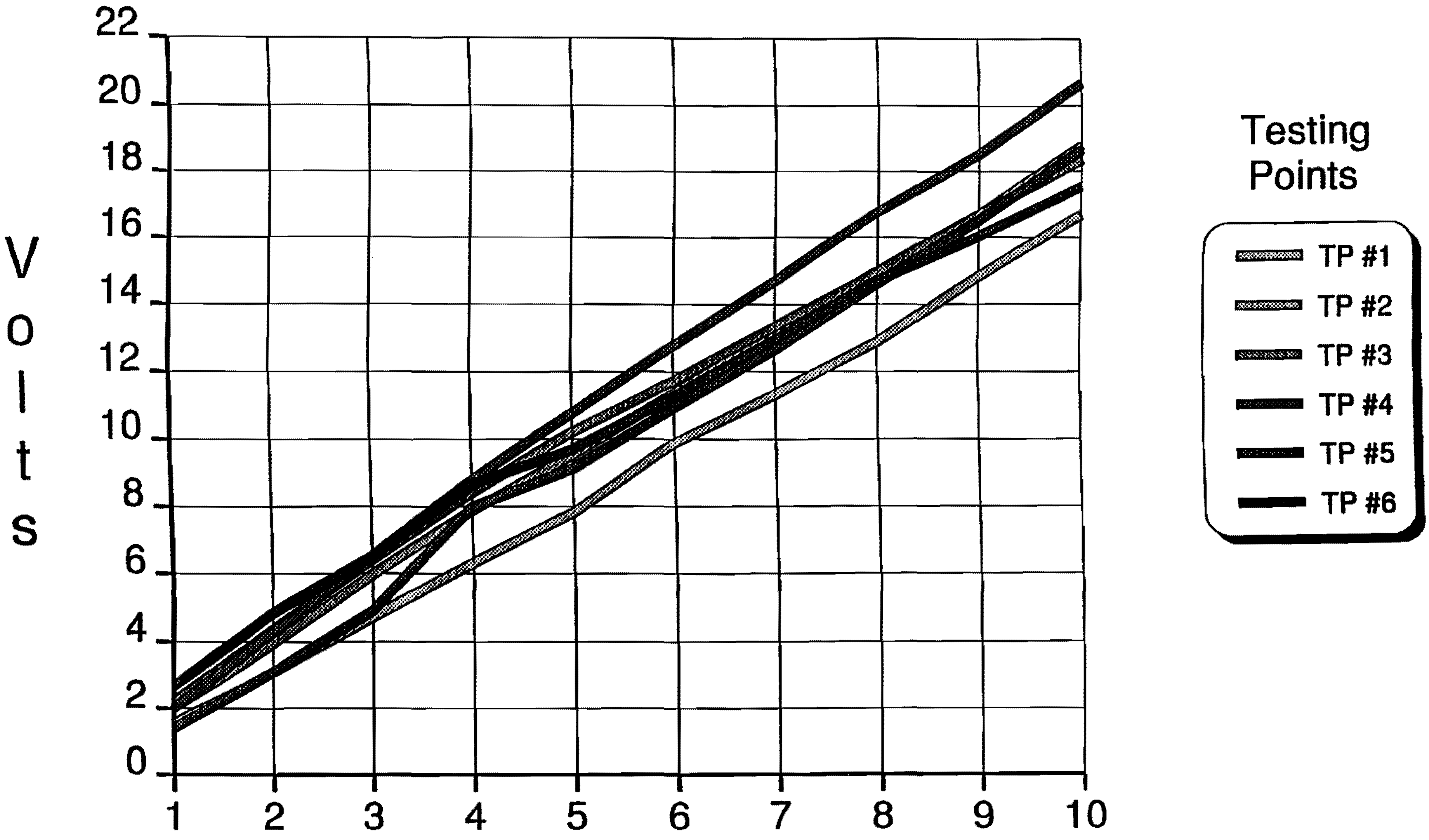

Figure 9. Linearity Test of Temporary Piezo Strip Axle Sensor

FIELD TESTING

Following the laboratory testing a prototype WIM system was fabricated using multiple temporary piezo axle sensors, an interface unit containing boards for processing the output from the sensors, and a portable IBM PC compatible microcomputer. Figure 10 illustrates the system.

Two different test trucks were used in the data collection at each of eight sites. The test trucks were a two axle single unit truck and a five axle tractor/semitrailer loaded as indicated in Figure 11. The eight sites varied in profile from smooth to rough. Figure 12 shows the measured profile for one of the smooth pavement sections. Figure 13 illustrates the measured profile for one of the medium-smooth pavement sections. Figure 14 gives the measured profile for one of the rough pavement sections.

The array of piezo axle sensors was installed in a lane on each section of pavement. Each test truck was then passed over the sensor array three times each at 10, 40, and 60 miles per hour (mph).

Typical results are shown in Figures 15 through 21 for one pass of each truck through a medium-smooth pavement section. Each of these figures illustrates the oscillation of one of the five axles of the test truck as it passes over the array of sensors. These results correspond well to data acquired in other similar research as well as vehicle simulation outputs.

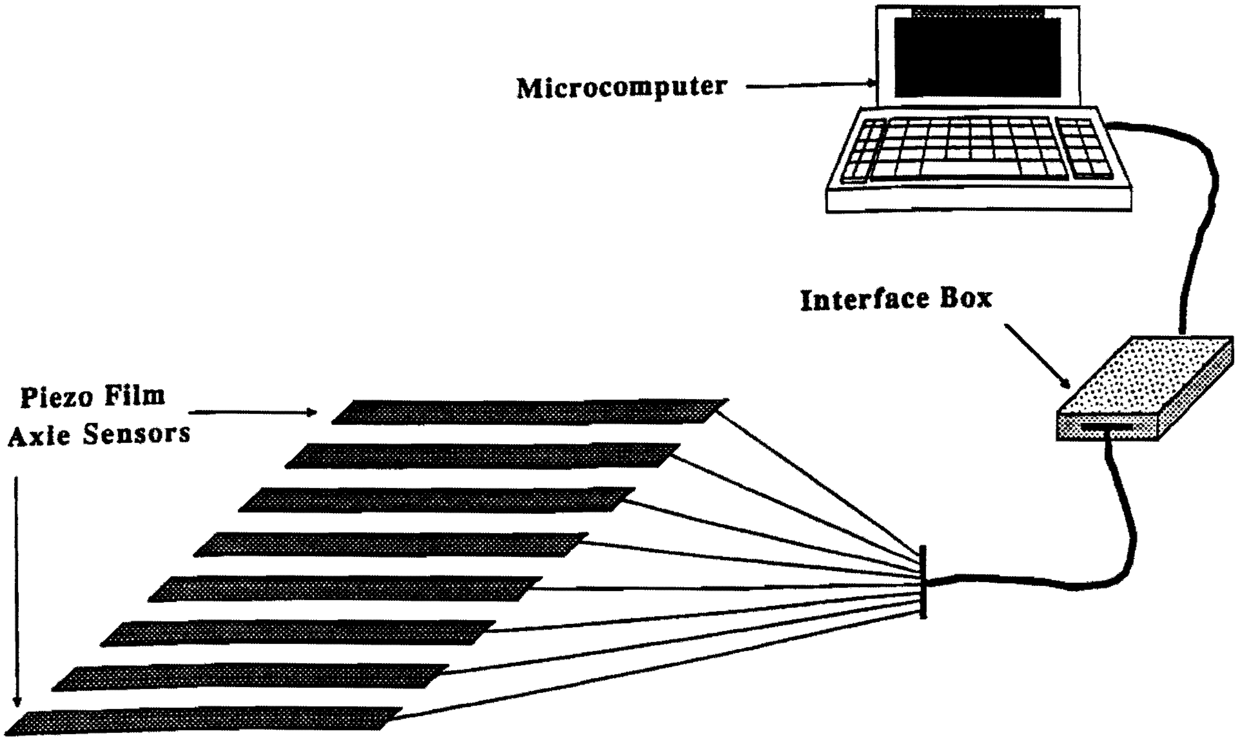

Figure 10. WIM System Configuration.

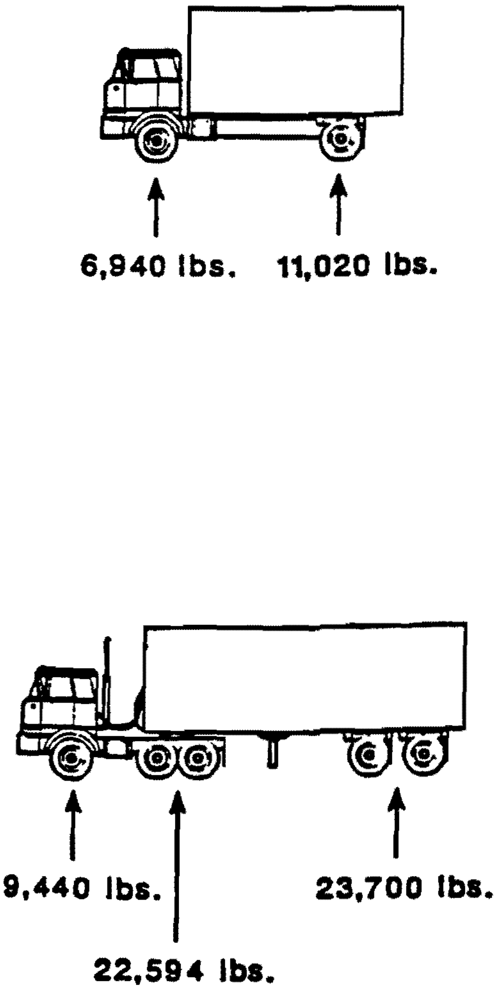

Figure 11. Loading Levels of Test Trucks.

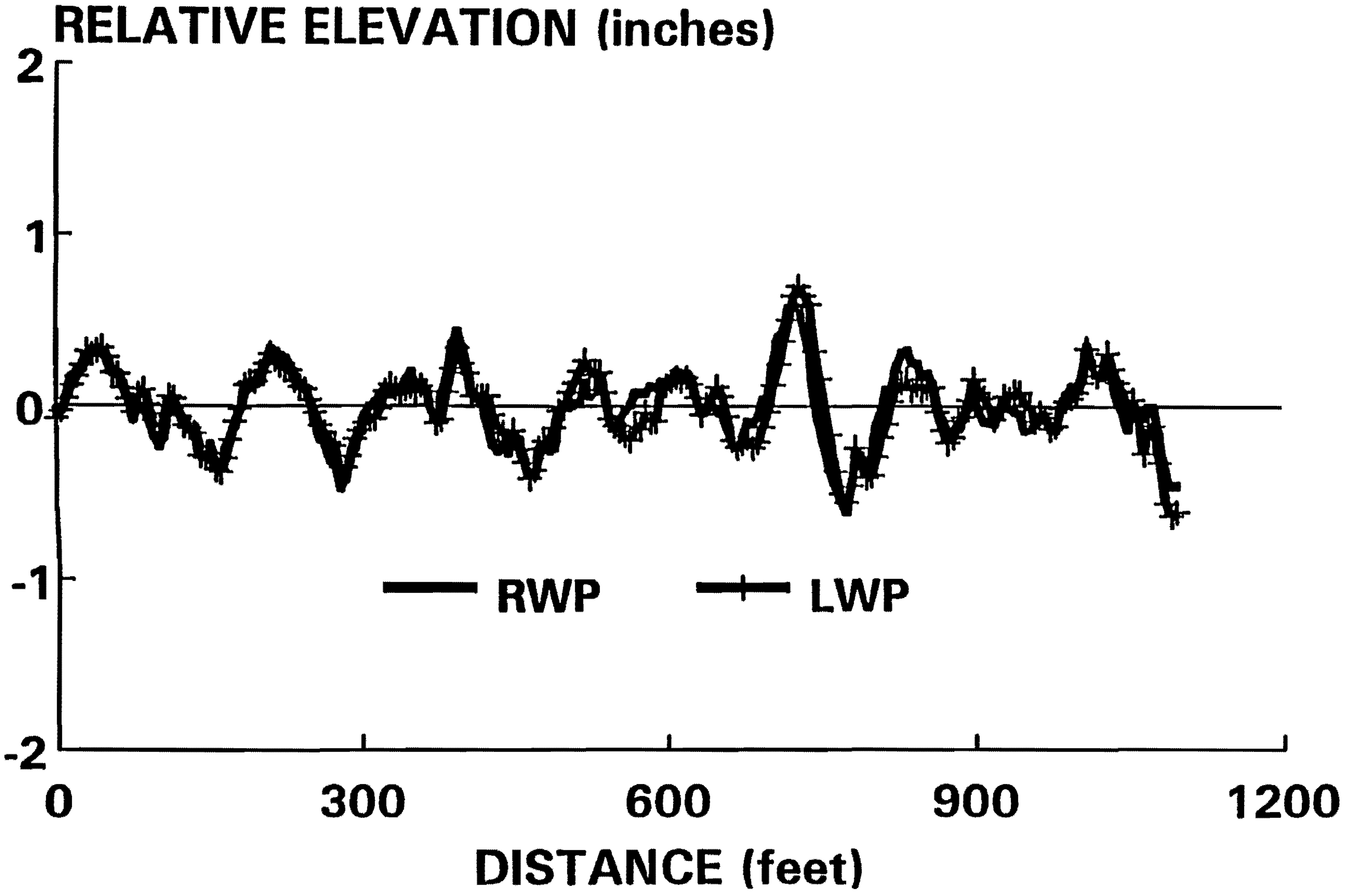

Figure 12. Measured Pavement Profile for Typical Smooth Pavement Section.

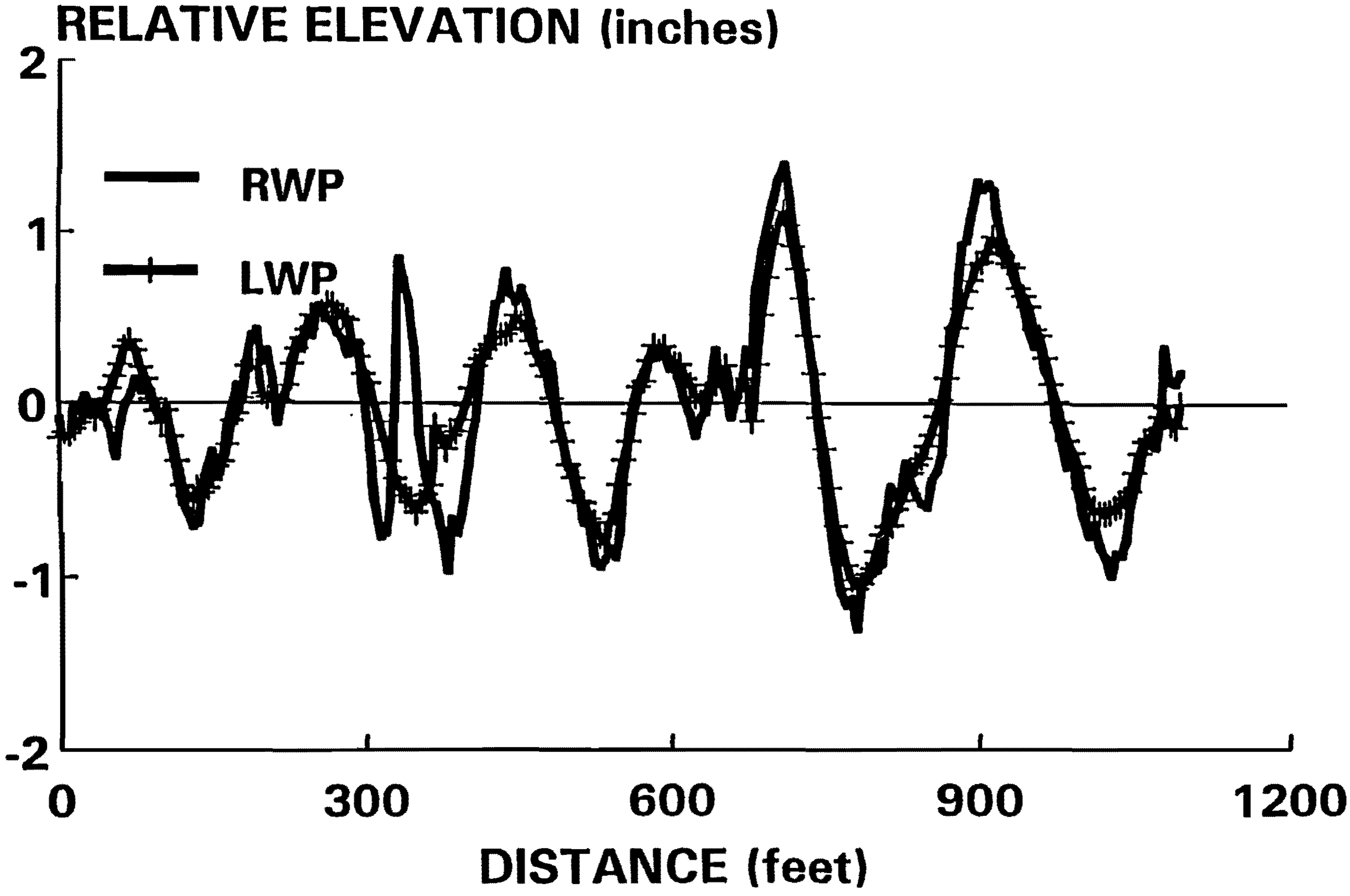

Figure 13. Measured Pavement Profile for Typical Medium-Smooth Pavement Section.

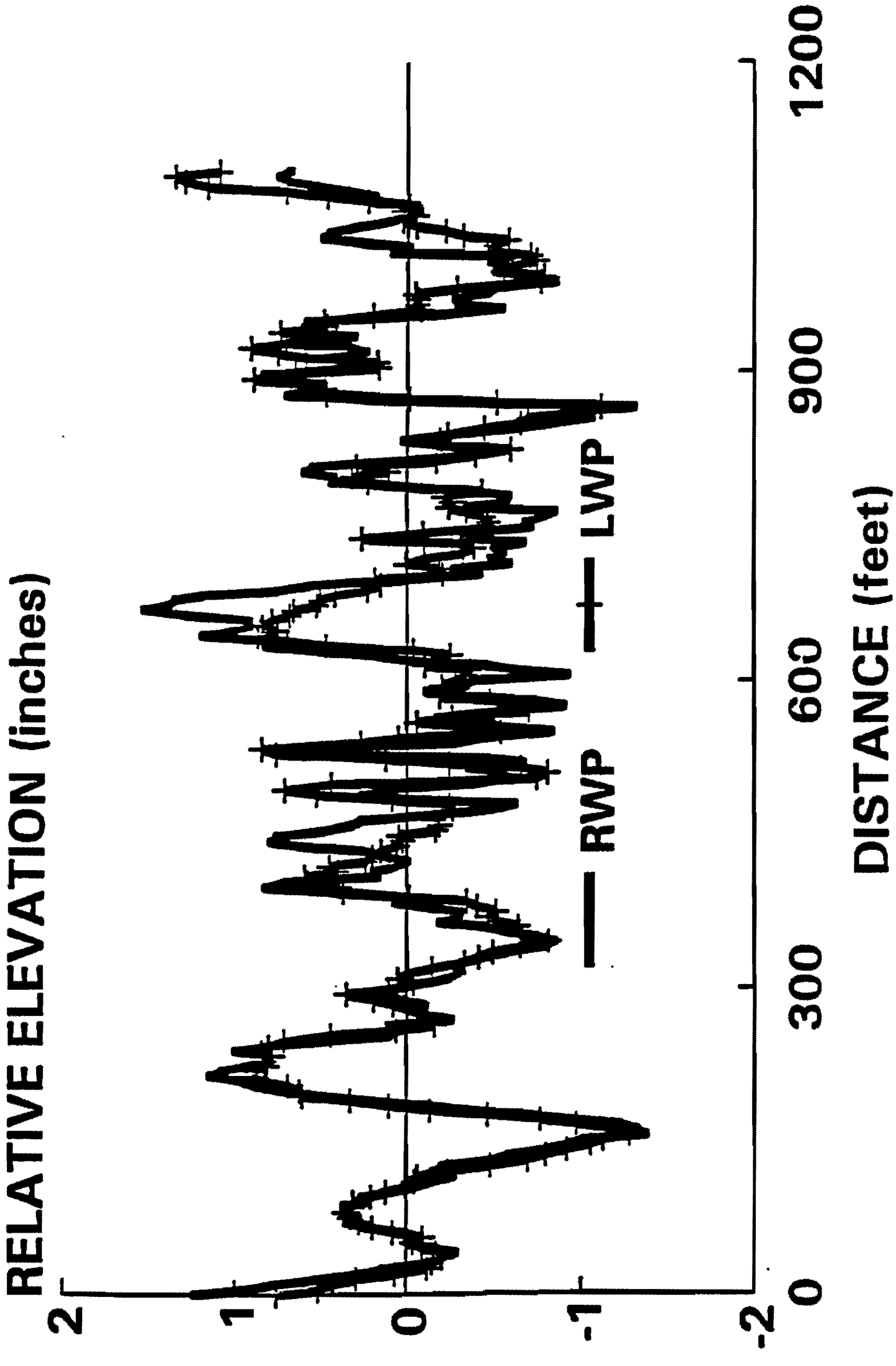

Figure 14. Measured Pavement Profile for Typical Rough Pavement Section.

```
SIGNAL

STRENGTH
       |
   150 +
       |
       |
       |                                               *         *
       |                      *                             *         *
   100 +  *    *                                  *
       |                           *    *
       |            *    *                   *
       |
       |
    50 +
       |
       |
       |
       |
     0 +
       |
       ---+----+----+----+----+----+----+----+----+----+----+----+----+--
          1    2    3    4    5    6    7    8    9   10   11   12   13

                                        SENSOR
```

Figure 15. Typical Response Pattern for the Steering Axle of the Two Axle Single Unit Test Truck on a Medium-Smooth Pavement Test Section.

```
SIGNAL
STRENGTH

       |
   300 +
       |
       |                                                         *
       |                           *
       |                 *              *                   *
   200 +  *                   *              *    *
       |
       |       *                                                      *
       |
       |                                               *
   100 +            *
       |
       |
       |
       |
     0 +
       |
       ---+----+----+----+----+----+----+----+----+----+----+----+----+--
          1    2    3    4    5    6    7    8    9   10   11   12   13

                                       SENSOR
```

Figure 16. Typical Response Pattern for the Rear Axle of the Two Axle Test Truck on a Medium-Smooth Pavement Test Section.

```
 SIGNAL

 STRENGTH


        |
    200 +
        |
        |
        |                                                         *
        |                                                    *
        |                 *         *                                  *
        |       *                             *         *
        |  *         *         *         *         *
    100 +
        |
        |
        |
        |
        |
        |
        |
      0 +
        ---+----+----+----+----+----+----+----+----+----+----+----+----+--
           1    2    3    4    5    6    7    8    9   10   11   12   13

                                        SENSOR
```

Figure 17. Typical Response Pattern for the Steering Axle of the Five Axle Tractor/Semi-Trailer Test Truck on a Medium-Smooth Pavement Test Section.

```
SIGNAL
STRENGTH

    |
300 +
    |                           *
    |                                               *    *
    |                                *         *
    |                                                         *    *
200 +       *                             *
    |  *         *    *    *
    |
    |
    |
100 +
    |
    |
    |
    |
  0 +
    |
    ---+----+----+----+----+----+----+----+----+----+----+----+----+--
       1    2    3    4    5    6    7    8    9   10   11   12   13

                                    SENSOR
```

Figure 18. Typical Response Pattern for the Second Axle of the Five Axle Tractor/Semi-Trailer Test Truck on a Medium-Smooth Pavement Test Section.

```
SIGNAL

STRENGTH

       |
   300 +
       |                                                    *
       |                           *
       |                                *    *    *    *         *
       |                 *    *                                       *
   200 +  *    *
       |            *
       |
       |
       |
   100 +
       |
       |
       |
       |
     0 +
       |
       ---+----+----+----+----+----+----+----+----+----+----+----+----+-

          1    2    3    4    5    6    7    8    9   10   11   12   13


                                       SENSOR
```

Figure 19. Typical Response Pattern for the Third Axle of the Five Axle Tractor/Semi-Trailer Test Truck on a Medium-Smooth Pavement Test Section.

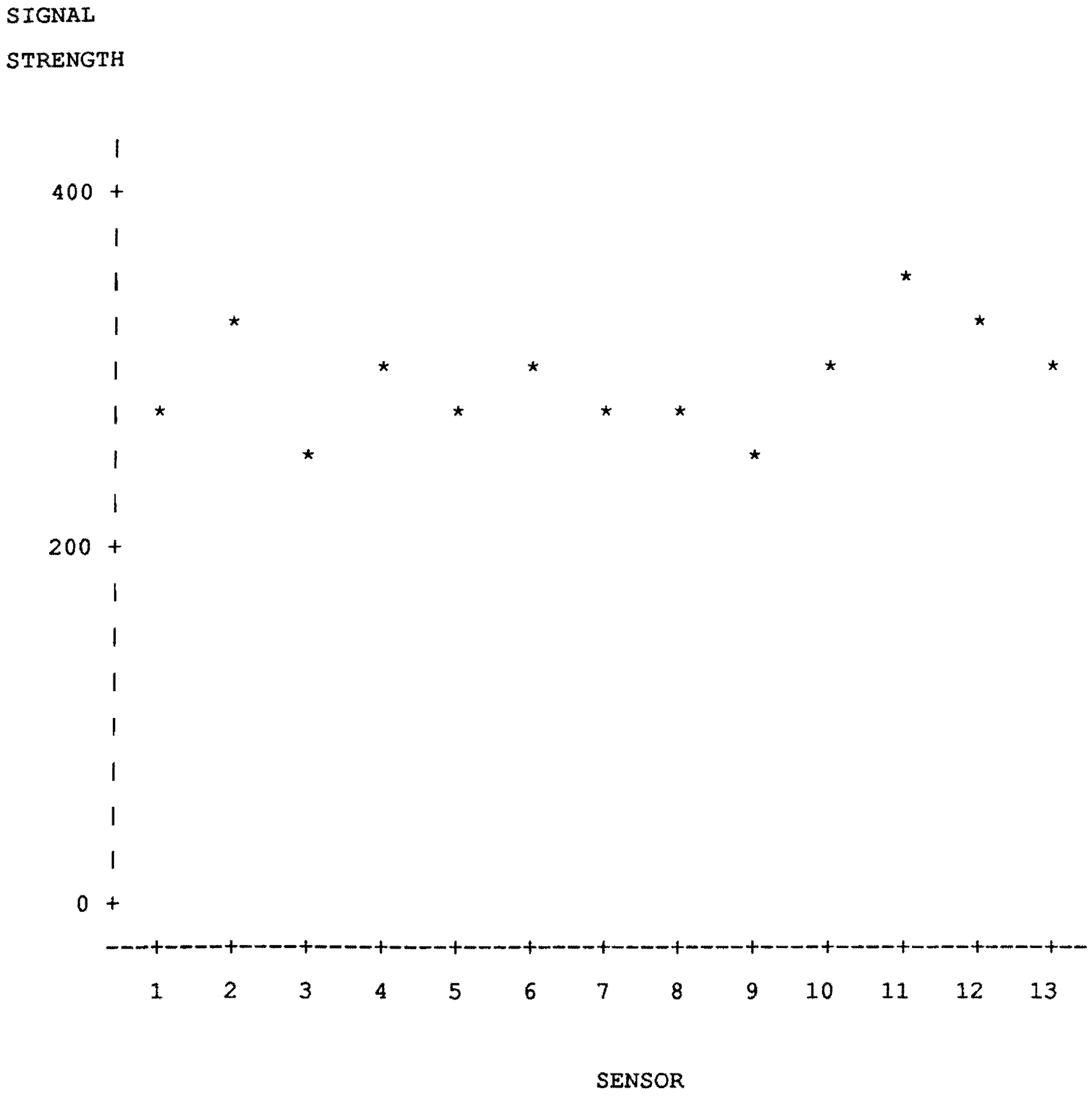

Figure 20. Typical Response Pattern for the Fourth Axle of the Five Axle Tractor/Semi-Trailer Test Truck on a Medium-Smooth Pavement Test Section.

```
SIGNAL
STRENGTH

       |
   300 +
       |
       |
       |
       |                           *                                  *
   200 +  *                             *
       |       *    *    *                                  *    *
       |                      *              *    *    *
       |
       |
   100 +
       |
       |
       |
       |
     0 +
       |
       ---+----+----+----+----+----+----+----+----+----+----+----+----+---
          1    2    3    4    5    6    7    8    9   10   11   12   13

                                       SENSOR
```

Figure 21. Typical Response Pattern for the Fifth Axle of the Five Axle Tractor/Semi-Trailer Test Truck on a Medium-Smooth Pavement Test Section.

CHAPTER 5. CONCLUSIONS AND RECOMMENDATIONS

Laboratory and field testing of the piezo film weighmat and axle sensors indicate that this technology is useful for WIM applications. A complete system that includes any of the sensors, an interface unit, and an IBM PC compatible portable microcomputer was developed. Efforts were focused on the development of a low cost WIM system based on an array of five piezo film axle sensors per lane. This low cost WIM system was evaluated and weighing algorithms were developed for the purpose of weighing and classifying vehicles at highway speeds. After a final and successful demonstration of the system's capabilities to TxDOT personnel on Interstate Highway 45 near Huntsville, Texas, the system was submitted to TxDOT for further evaluation.

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