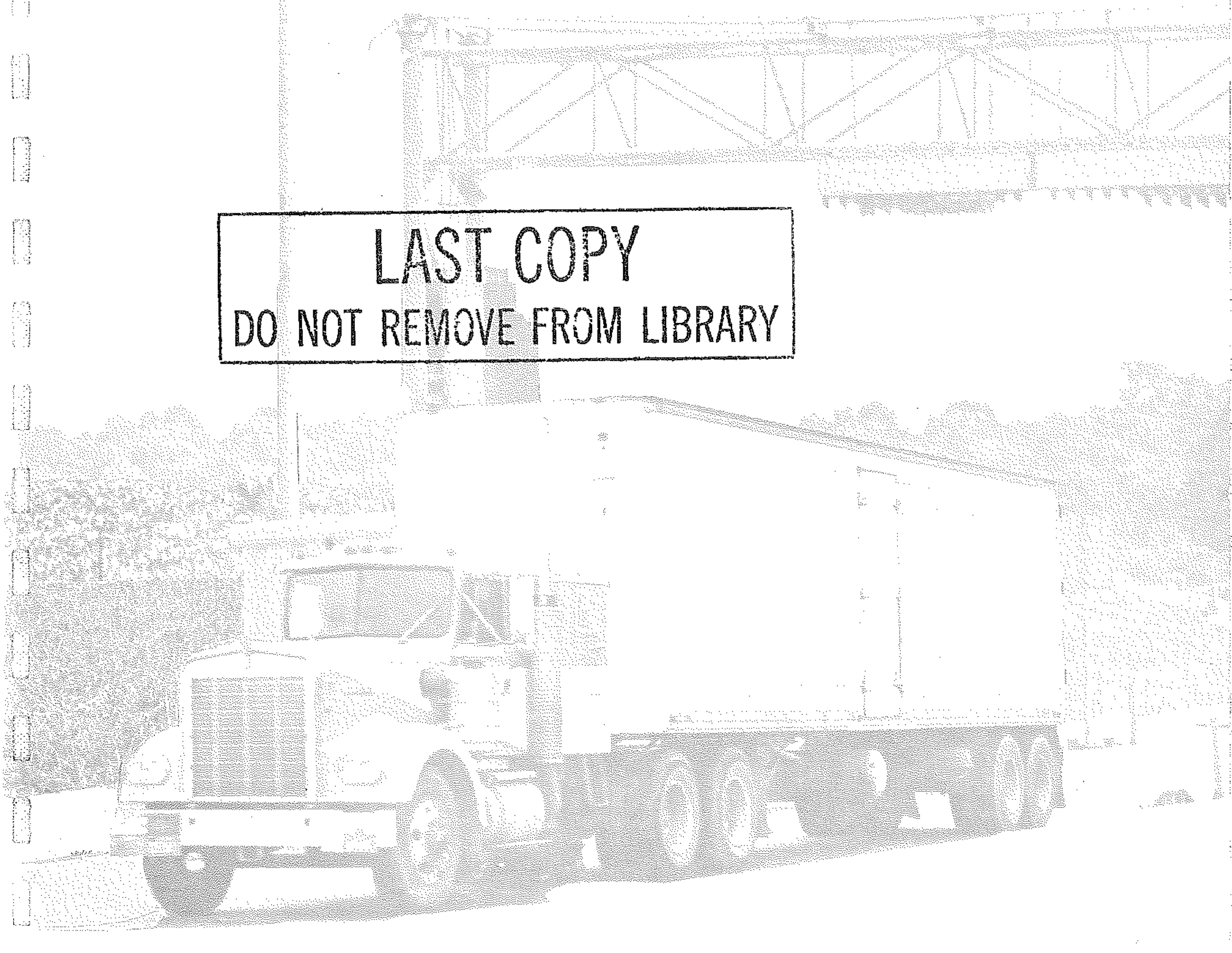
AUTOMATIC WEIGHING OF VEHICLES IN MOTION AND COLLECTION OF TRAFFIC DATA BY ELECTRONIC METHODS



MICHIGAN DEPARTMENT OF STATE HIGHWAYS AND TRANSPORTATION

AUTOMATIC WEIGHING OF VEHICLES IN MOTION AND COLLECTION OF TRAFFIC DATA BY ELECTRONIC METHODS

Final Report on a Highway Planning and Research Investigation
Conducted in Cooperation with the U.S. Department of Transportation
Federal Highway Administration

Research Laboratory Section
Testing and Research Division
Research Project 52 F-26
Research Report No. R-892

Michigan State Highway and Transportation Commission
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John P. Woodford, Director
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A few key individuals must be singled out for special recognition for their major contributions to the study. These are G. A. Otto and L. E. DeFrain of Michigan's Highway Research Laboratory, J. Galbraith of Philco-Ford's Communications and Electronics Division, and J. Bassett of Epsco's Advanced Concept Engineering Division.

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From the Highway Research Laboratory - E. A. Finney and L. T. Oehler, former and present heads of the Laboratory; P. Milliman, Supervising Engineer of Physical Research; P. G. Gray, Physical Research Engineer; L. F. Holbrook, Supervisor of Statistics and Data Processing; J. R. Darlington, Data Systems Specialist; C. J. Arnold, Supervising Engineer of the Structures Group; and M. J. Fongers and W. E. Casey of the Instrumentation Group.

From the Federal Highway Administration - R. C. Hopkins, then Chief of the Electro-Mechanical Research Branch, Traffic Systems Research Division.

From the Philco-Ford Corporation - J. Z. Grayum, Physicist; J. Mathias, Mechanical Engineer; and S. McConnell, Computer Programmer.

CONTENTS

SUMMARY

This report is concerned with the development of an electronic system to weigh and dimension trucks moving at near highway speeds. The system is installed in an area used for the normal mechanical weighing and manual dimensioning of highway truck traffic.

The benefits from the electronic system are: a reduction in the time required for legal trucks to pass through the checkpoint and the ready accumulation of data for further analyses.

Also described is a classification system installed on a bridge on westbound I 94 to categorize vehicles in different speed bands as trucks (high vehicles) or cars (low vehicles) using ultrasonic transducers.

The Department's interest in electronic weighing began in 1952 with the construction of "electronic loadometer plates" and was continued in 1958-59 by the construction and experimentation with a strain gage load cell type scale at the Department's Fowlerville weigh station.

As a result of the Fowlerville project, the Department decided to proceed with the construction of a more extensive weighing system.

In 1960, a proposal was completed and approved by the Federal Highway Administration as a cooperative project under the Highway Planning and Research Program. This project was completed in several phases.

The first phase was a feasibility study to determine the probability of success of a complete system. A contract was awarded to Epsco Inc., then of Cambridge, Massachusetts. Their conclusion was that the project was feasible.

The next phase, also performed by Epsco Inc., was the construction of a "breadboard" installation on I 94 near Jackson, Michigan. Data were collected on magnetic tape and processed by an off-site computer.

The following phase, performed by Department personnel, was to refurbish the installation and reduce vibrations in the scale platforms, which resulted in improved accuracies. As a result of this phase, a decision was made to go ahead with a fully automated system with real time computations.

In December 1964, a contract for this system was awarded to Philco, a subsidiary of Ford Motor Co. The work was completed in February 1966.

The final phase was done by Department personnel as a testing and operational program. Final one standard error precisions were as follows: axle weight, 682 lb; height, 5.0 in.; width, 2.8 in.; and axle spacing, 1.5 in. Both vehicle speed and classification and vehicle survey subsystems were found to operate satisfactorily and with adequate reliability. A 16-mm movie of the completed system has been prepared and is available from the Federal Highway Administration.

Two serious deficiencies in the system design were noted in the testing and operational phase. Mechanical tapeswitches used to determine when axles were on the scale platforms failed to perform satisfactorily at all times. As a stop-gap measure, these were finally replaced by photo-electric switches. This allowed the completion of the testing, but is not the final answer. The other problem was protection against lightning damage. Again, an interim procedure was followed. Although the report does not explicitly mention alternatives to prevent these problems from occurring, they are surmountable by proper system design.

The reader is reminded that this system was designed approximately one decade ago. Since that time there have been rapid advances in technology, particularly in electronics. For example, in many cases large scale integration has replaced discrete solid-state components resulting in more computer power per dollar. The computer used in this system is no longer manufactured, but other mini-computers are available that are faster and smaller. Even smaller computers, called micro-computers, might be useful in electronic weighing and dimensioning systems. Also, the development of portable electronic scales merits consideration, compared to the large permanent scale pits used in the reported project.

I

INTRODUCTION

The highway transportation problem in the United States becomes more difficult and critical each day. The last few years have seen an annual addition of 4,500,000 vehicles to the Nation's streets and highways--an average net gain of over 12,000 vehicles each day. Lending further urgency to the problem is the fact that this already tremendous growth rate is on the increase.

If the highways are to continue to provide a safe and economical surface transportation system, under a condition of continuously increasing traffic pressure, every effort must be made to insure that the present system and future additions are utilized as efficiently as possible. Control procedures aimed at achieving optimum traffic flow require continuously current, quantitative description of the elements making up the traffic stream, and the flow characteristics of the composite stream. Obtaining the necessary quantitative description requires the ability to automatically sense and record the physical characteristics (weight, dimension, type, etc.) of the individual vehicles in the traffic stream, plus their in-stream performance characteristics.

The system described here is the result of a research and development program carried out by the Research Laboratory of the Michigan Department of State Highways and Transportation in cooperation with the Federal Highway Administration. The contents of this report reflect the views of the authors who are responsible for the facts and the accuracy of the data presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration. This report does not constitute a standard, specification, or regulation.

When the project was initiated in 1952, its goal was to determine the accomplishments of others to that date, to keep abreast of subsequent progress primarily through the literature, and to begin low-key experimentation.

Subsequently, the aim became the realization of the fully defined and operating system to automatically sense and record all pertinent information from in-motion vehicles.

The original objectives of the project as stated in the initial proposal, dated July 1960 (Table 1), were as follows:

1) Develop a complete electronic system for the automatic weighing of vehicles in motion, and collection of certain traffic information, the transmission of the information to a central location, and at that location, auto-

TABLE 1
OUTLINE OF PROJECT OBJECTIVES

	PROPOSAL	
I	Feasibility Study	
II	Final Design, Engineering, Specifications, and Cost	July 1960
III	Complete System Installation	

FEASIBILITY STUDY by Epsco, Inc.	Dec. 1960 to Mar. 1960

The results of the feasibility study indicated that an improvement in program efficiency would result from combination of Parts II and III, and a supplemental proposal was written reorganizing the problem approach:

SUPPLEMENTAL PROPOSAL	
Part A - Experimental Field Test Program	
Part B - Automatic Recording and Data Processing Installation	July 1961

PART A by Epsco Inc.	Sept. 1961 to Mar. 1964

The desired measurement accuracies were not attained in Part A, and thus an extension of the project was proposed, designated "Post Part A," to attempt accuracy and durability improvements:

	POST PART A by Michigan Department of State Highways and Transportation	Sept. 1963 to Feb. 1965
I	Accuracy Improvement	
II	Durability Improvement	

SPECIFICATIONS FOR PART B by Michigan Department of State Highways and Transportation	Sept. 1964

PART B Completion of System by Philco-Ford Corp.	Mar. 1965 to Feb. 1966

	PART C	
I	One year of experimental operation of system by Michigan Department of State Highways and Transportation	1966-67
II	Two year extension to measure 1,000 vehicles and evaluate results	1967-69

matically condition the measured data into proper formats for subsequent analysis.

2) Develop a complete design with appropriate drawings, charts, specifications, instructions, etc., for all equipment, its installation, and process involved, together with items of cost, and ready to submit to prospective bidders for the construction of other such systems.

3) Have a complete automatic system in full operation for a period of not less than 30 days to insure the Department that the system is operating in accordance with the system requirements.

4) Operate the system as a research installation for a period of at least one year in order to develop optimum operating and data acquisition procedures and in order to realize design improvements in future systems.

The Michigan system is a prototype and subject to certain limitations, and although it does sense all of the needed information from moving vehicles, it is still necessary to disturb the traffic stream somewhat. Vehicles (trucks) which are to be weighed and measured dynamically are diverted from the traffic stream to a special one-half mile long evaluation path, which parallels the main traffic stream. Ideal future systems will be those which sense all physical and flow characteristics from vehicles moving in their normal manner in a traffic stream environment. Such systems are still in the future, but off-stream systems such as the one reported here play a significant part in their evolution.

As a final introductory note, the reader is cautioned not to be misled by the many problems encountered in assembling and operating this system. Such problems are characteristic of first, or prototype, systems. It is because of their characteristic troublesomeness that prototypes are built--to discover, isolate, and eliminate bugs, quirks, and weaknesses; rarely is a designer able to foresee all of the problems that might occur in a large complex system.

HISTORICAL BACKGROUND

Michigan first became interested in the possibilities of dynamic vehicle weighing in 1952, and at that time a research project was initiated.

In 1952-53, experiments were conducted with "electronic loadometer plates." These were curved steel or aluminum plates with a strain gage network on their concave underside. As a vehicle axle passed slowly over the convex surface of the plates, the downward deflection caused tensile strain in the undersurface. This strain was sensed and averaged by the strain gage network, then converted to weight by means of strain-load calibration curves. These plates were used in one field study and performed quite well for very slowly moving axles. However, as this approach to the in-motion weighing problem was obviously not feasible for fast-moving vehicles, it was abandoned. Little additional dynamic weighing work was done until 1958.

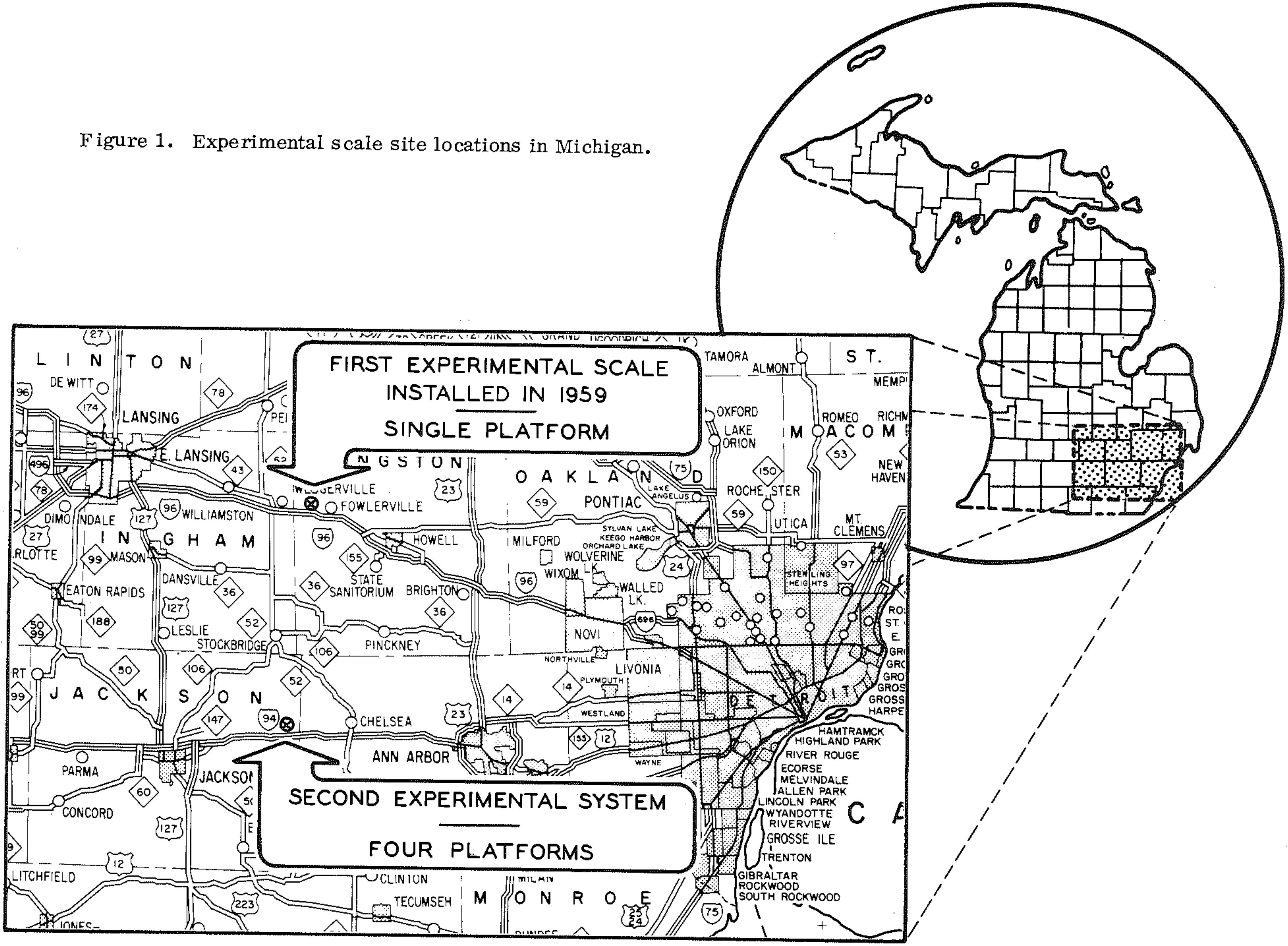
In early 1958, plans and specifications were completed for a proposed experimental strain gage, load-cell type scale. The resulting scale was installed in an approach ramp to the Department's Fowlerville weigh station during the winter of 1958-59. During 1959 and early 1960, experiments were performed with this installation to investigate the effects on accuracy of axle type, vehicle speed, load cell placement, platform restraints, platform hold-down configurations, magnitude of hold-down forces, platform configurations, stiffness, etc.

As a result of this work, the Department decided to proceed with a more extensive system.

In July 1960, a proposal was completed and submitted to the Federal Highway Administration for consideration, under the Highway Planning and Research Program, as a cooperative project for development of a complete, operational, dynamic vehicle weighing system. At their suggestion, this proposal was expanded to include measuring moving vehicles, as well as weighing them.

After obtaining FHWA approval, the proposal was circulated to a number of companies engaged in electronic system work, inviting them to submit performance proposals. In the fall of 1960, the proposal submitted by Epsco, Inc., of Cambridge, Massachusetts, was accepted and they were awarded a contract for a feasibility study to determine the probability of success of a complete weighing and dimensioning system. In March 1961, Epsco reported the results of their study (1). Their conclusion, supported by experimental data, was that the proposed system was fully feasible. Consequently, a second contract was awarded to Epsco in July 1961 for fabrication and installation of a measuring and weighing system at the Grass Lake weigh station on I 94 in Southern Michigan (Figs. 1 and 2).

Figure 1. Experimental scale site locations in Michigan.



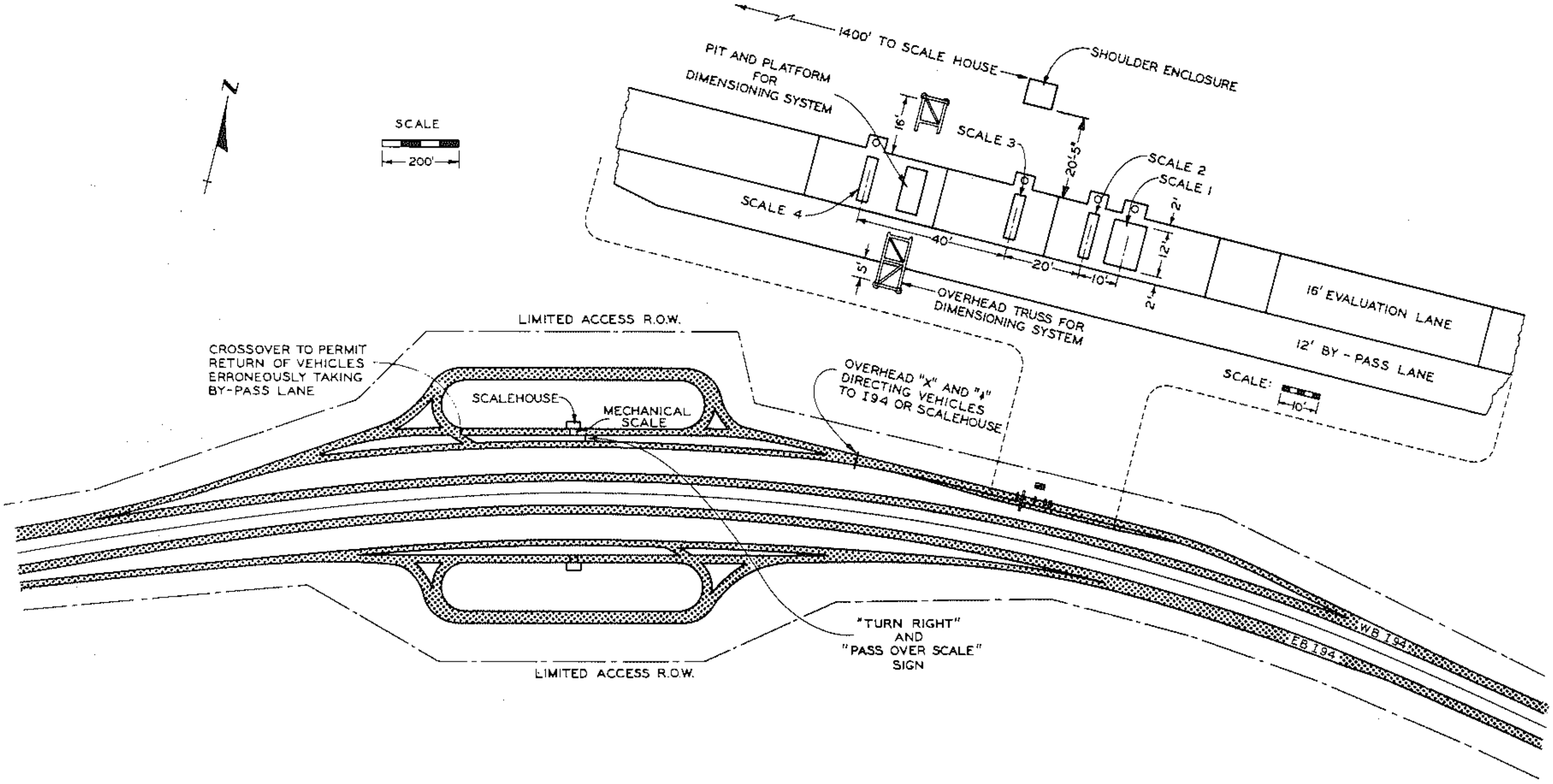


Figure 2. Final electronic truck weighing and dimensioning site layout.

As the FHWA had reservations concerning the degree of success attainable, they limited the scope of this second contract to a "breadboard" system. They reasoned that full operation and accuracy should be demonstrated before installing a finished system that would include an on-site computer, printout equipment, closed circuit television, control and operating consoles, etc. This limited contract was completed and reported by Epsco in March 1964 (2). The results were disappointing in that target accuracies were not achieved and physical plant condition and much of its design were marginal at best.

To rectify the physical plant deficiencies and attain what were considered reasonable goals, "Post Part A" was proposed by the Department--to be performed by the Department. This proposal was approved by the FHWA in September 1963. Its purpose was to improve the accuracy, reliability, durability and safety of an already existing measurement system. Post Part A was completed in February 1965 with a greatly improved, much more accurate system. On the basis of the Post Part A results, the FHWA approved continued progress on the project (3).

The Department prepared complete specifications for a Part B phase, and invited proposals from a number of concerns engaged in electronic systems work. Part B requirements included replacement or configuration modification of most of the breadboard system components necessary to the fully automatic system.

In December 1964, the Part B contract was awarded to Philco-Ford Corp. They began their work on the system in March 1965 and completed it in February 1966 (4).

At the completion of Part B, the Department initiated the final phase of the program, Part C. This consisted of an extensive period of research in the operation of the system to study and improve its functioning by making any necessary modifications, developing operational procedures, and obtaining a comprehensive quantitative definition of all system measurement capabilities. This report describes the present state of the system with recommendations for future research and development.

ACHIEVEMENTS OF OTHER AGENCIES

A vast amount of work has been performed on in-motion weighing since the pioneer Shirley Highway installation by Normann and Hopkins (5) in 1951.

A score of states have worked on various aspects of the problem. An equal or greater number of commercial concerns have reported on their activities in the area or have equipment commercially available. Many foreign countries have experimented with dynamic weighing and a few have actual in-service installations.

A project of the University of Kentucky involved the construction, installation, testing, and performance analysis of three types of dynamic electronic scales; the Taller-Cooper, the Broken Bridge, and the Beam Type scale (6).

The Center for Highway Research, University of Texas, has reported on a portable electronic scale for weighing vehicles in motion (7).

European weighing systems have been installed; in particular, in Great Britain (8), Germany (9), and Sweden (10).

A portable weight transducer was developed by the Texas Highway Department in cooperation with the University of Texas. In 1968, after improvements and modifications, a satisfactory product emerged (11).

Most of this work has concerned installations of the load-cell-supported platform type of scale. There have also been studies with strain gage instrumented platforms, and broken-bridge type load cell supported platforms, plus a number of analytical studies which have attempted to establish mathematical models and definitions for the dynamic scale - vehicle interrelationship. The majority of these studies have considered load cell supported platforms, involving commercial, educational, and governmental agencies both foreign and domestic, and have all been similar in approach, have encountered similar problems, and have produced similar conclusions.

II

TECHNICAL DESCRIPTION OF THE SYSTEM

Figure 3 should enable the reader to better understand the various subsystems and their function in the total system operation. It is a physical layout of the entire system showing all system components and their locations along the path taken by the vehicle being weighed, measured, and classified. It also shows the site configuration of the standard Michigan weigh station into which the system was incorporated, and the non-standard bypass lane that was added.

Figure 4 is a functional block diagram of the weight, dimension, and survey subsystems, showing their functional components and the interconnections between the components.

The reader is advised to pause at this point and study Figures 3 and 4 as familiarity with them will greatly enhance understanding of the technical description that follows. Additional photographs of system components are located in the Appendix.

SYSTEM ELEMENTS

The overall, master system consists of four functional subsystems which are located in four separate areas as shown in Figure 3.

1) Evaluation Path - contains all sensors required to measure vehicle parameters (Fig. 5).

2) Shoulder Enclosure - contains necessary electrical power distribution panels and electronic signal conditioning equipment. It is a terminal for signal and power cables between the sensors and the 1,400 ft of buried cable to the scalehouse (Fig. 6).

3) Scalehouse - an all-season building used by the weighmaster. It contains the weigh bar for the mechanical scale adjacent to the building, along with office space, rest rooms, and a basement. A radio communication system, telephone, and PA system are also provided for the proper operation of the facility. It also contains the system control console, computer, and other input/output devices (Fig. 7).

4) Vehicle speed and classification sensors - located on a bridge 1-3/4 miles west of the weigh station, their signals are transmitted back to the scalehouse through buried cable (Fig. 8).

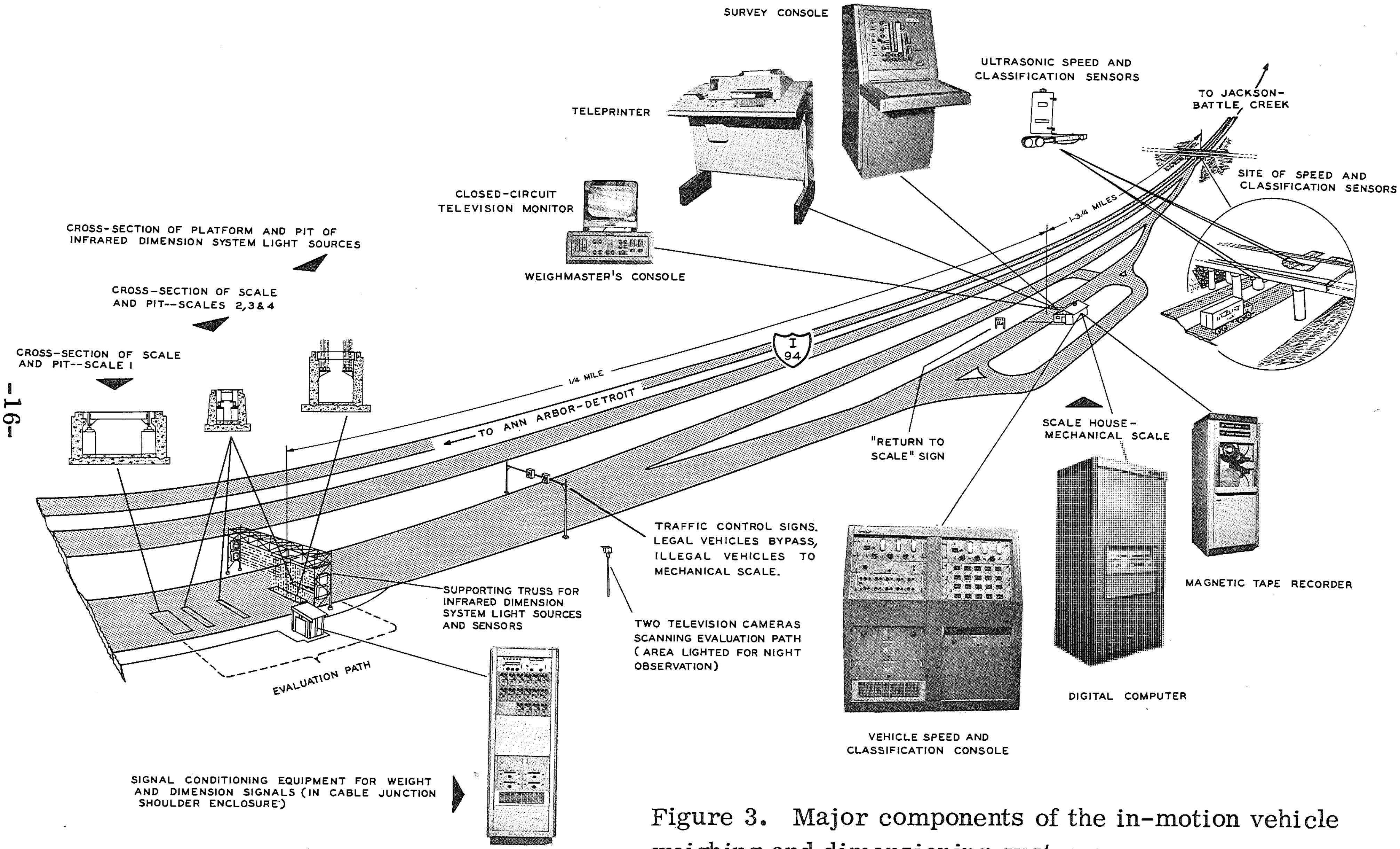


Figure 3. Major components of the in-motion vehicle weighing and dimensioning systems.

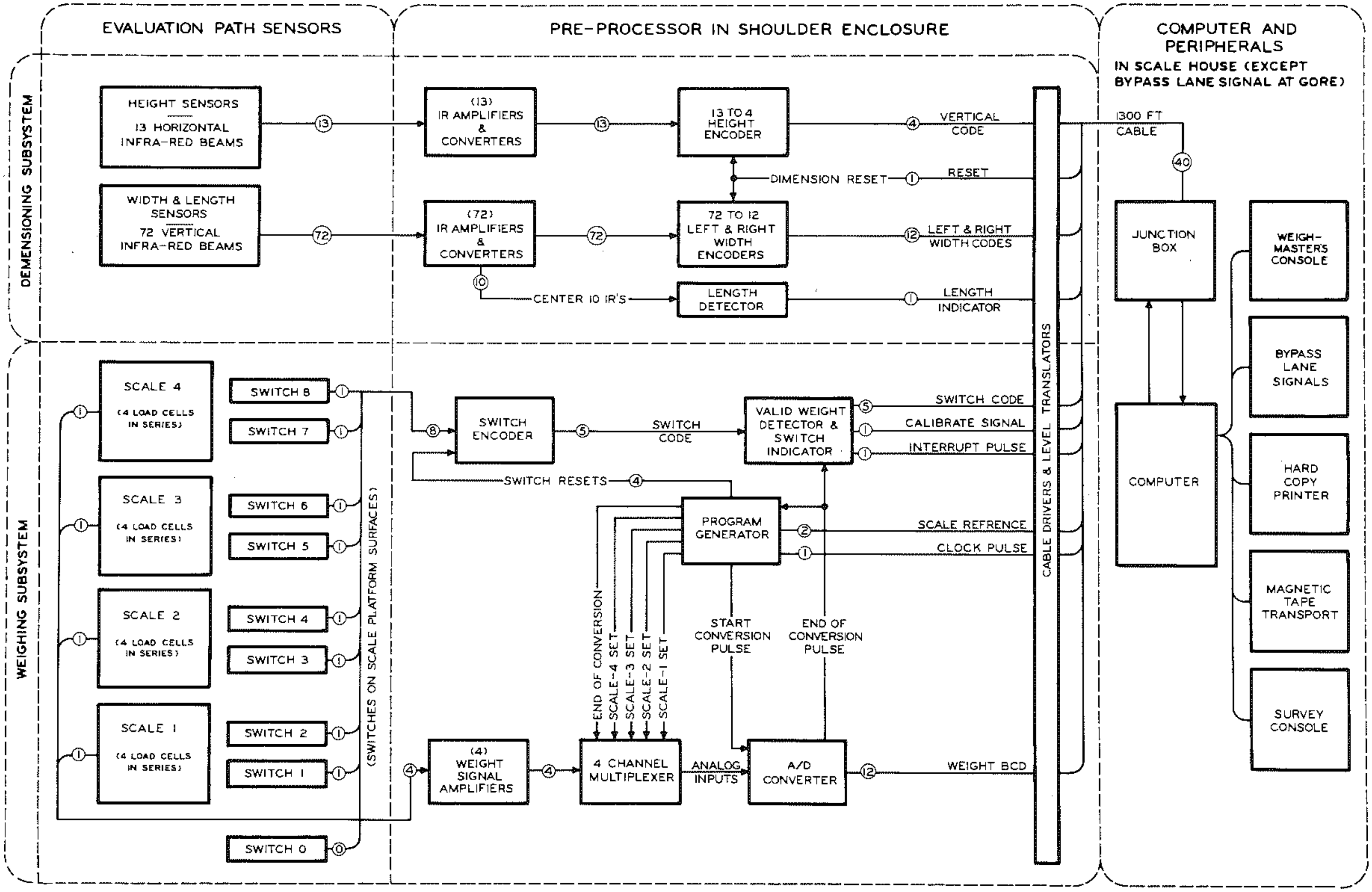


Figure 4. Functional components of the electronic weighing and dimensioning systems.

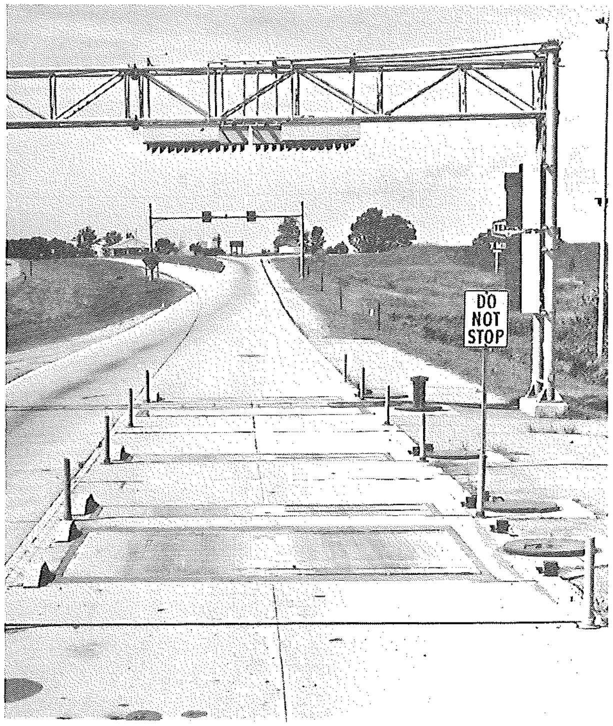


Figure 5. Vehicle evaluation path.

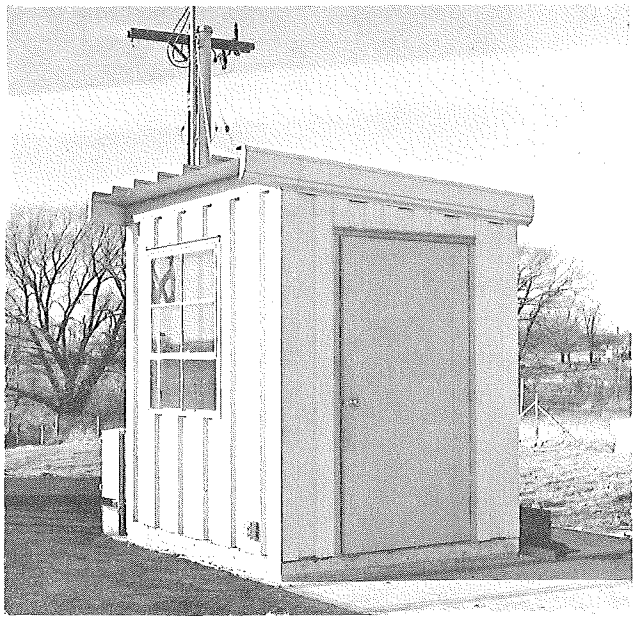


Figure 6. Shoulder enclosure serving as the junction and distribution point for all evaluation path power and signal circuits, and containing power supplies, amplifiers, and system preprocessing equipment.

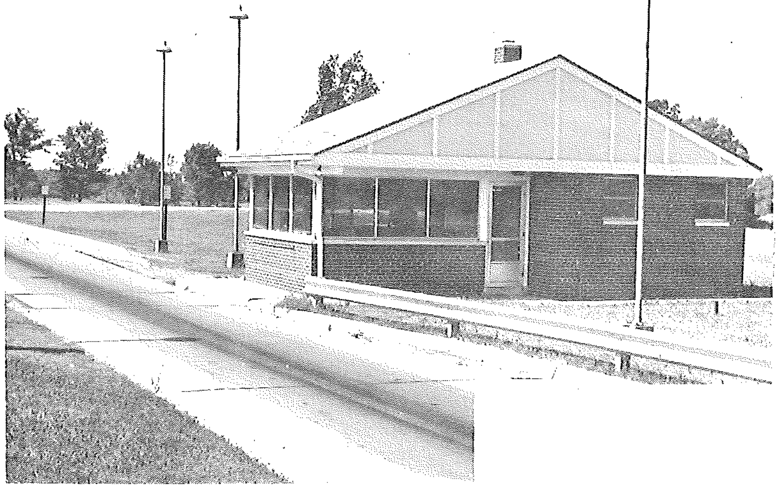
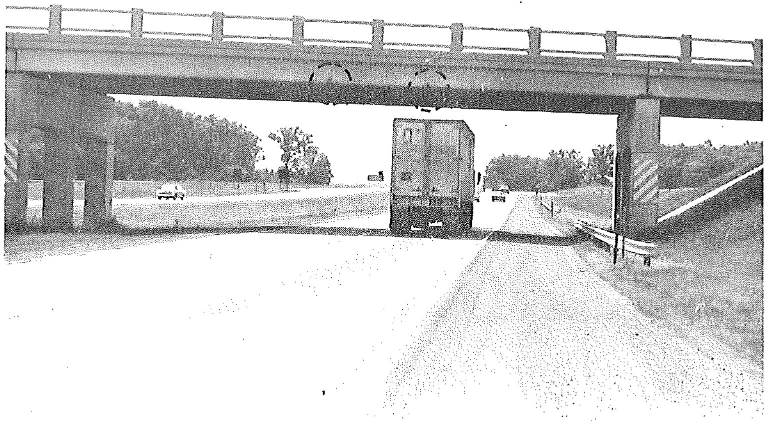


Figure 7. Scalehouse and mechanical scale for static axle weighing.

Figure 8. Vehicle speed and classification transducers (1/4 mile from the scales).



The overall, master system consists of four operational subsystems, as well.

1) Vehicle sensing transducers -

a) Four platform scales having four load cell transducers each, for the dynamic weighing of individual truck axles.

b) An array of infrared sources and detectors for the dynamic measurement of vehicle width, height, and length dimensions.

c) An array of infrared sources and detectors for determining the number and location of axles under dynamic conditions, and to insure on-scale weighings only.

d) An ultrasonic transceiver installation surveying freeway traffic. Measurement parameters are vehicle speed and classification (car or truck).

2) System Control -

a) A control console permitting the on-site weighmaster to operate and monitor system status.

b) Electronic logic, and equipment which transforms the transducer signals into digital codes for transmission to computer. This system monitors the operation of the system transducers and indicates any malfunctions.

3) The Computer -

a) Reads data obtained from system control, upon command, and makes decisions as to whether a vehicle is legal.

b) Informs the weighmaster of its decision and directs the driver to return to the highway or to the mechanical scales for static weighing and/or dimensional checks.

c) Monitors all transducer and control activities, up-dates its own internal clock, receives and transmits status commands to the weighmaster.

4) Input and Output Equipment -

a) A survey console permitting magnetic tape recording of visually sensed and manually entered vehicle data for off-site analysis.

b) The weighmaster's control console.

c) Computer controlled teletype for printing vehicle data. It can also be used to input computer commands. This device is also used for program development when the system is not in operation.

d) Computer activated traffic control signs.

e) A digital magnetic tape unit for storing vehicle data, program development, and program input.

f) A closed-circuit television system which allows the weighmaster to observe the vehicle evaluation path approximately 1/4 mile away.

g) A vehicle speed and classification console which includes equipment necessary to calculate, display, and record speed and vehicle type information for each of two traffic lanes.

SYSTEM OPERATION

In order that the reader may have a functional concept of the system objectives, a brief general description of normal system operation is given, followed by some more detailed explanation of individual components.

When the final axle of a truck passing through the evaluation area, delineated in Figure 3, leaves the last (fourth) scale platform the system computer makes a real-time computation to determine the truck's status; "legal" or "illegal." The computer is programmed such that oversize or overweight trucks are directed to the lane leading to the mechanical scales where the vehicle is statically weighed or manually measured (such measurements are necessary because in-motion measurements are not yet legally enforceable). If a truck leaving the evaluation path is fully legal it is directed to a scalehouse bypass lane which routes it directly back to the freeway.

When a violation is detected, the computer controlled teletypewriter produces a hard-copy printout for the scalehouse operator (weighmaster) prior to the arrival of the violating truck at the scalehouse. In addition, the weighmaster may obtain a hard-copy printout for any of the legal vehicles by depressing the HARD COPY switch on his control console.

The system is designed for the operation of the weighing and dimensioning subsystems separately or together. A truck is measured for maximum length, height, and width on the basis of the interruption pattern it presents to a vertical and horizontal infrared light beam array placed in its path. Thirteen horizontal beams are used to determine the maximum height of the truck. Similarly, 72 vertical beams are used to determine the maximum width of the truck. In addition, the center 10 vertical beams (five from the left, five from the right) are used in measuring truck lengths.

The weighing function of the system is accomplished by four electronic scales which are situated at center-to-center intervals of 10, 20, and 40 ft. All scales are 12 ft wide. The first scale encountered by a vehicle entering the system is 9 ft long in the direction of vehicle travel. This scale can determine weights of vehicle undercarriages incorporating up to three axles (singles, tandems, and tridems). The three remaining scales are each 3 ft long and determine single axle weights only.

A pair of tire-actuated, photoelectric switches are located on the surface of each scale platform to provide a basis for determining the location of axles in the system, the number of axles, the axle spacings, the vehicle speed, and the initiation of vehicle length measurements. A ninth switch located in front of the first scale provides for system turn-on when actuated by a vehicle's steering axle.

A vehicle speed and classification system, entirely separate from the weighing and dimensioning systems, was installed to classify all westbound vehicles as to car or truck and as to speed. The sensors for this system are located on the underside of a bridge approximately 1-3/4 miles downstream from the main system. Two sensors, detecting speed and height (high-low) are located in each of the two lanes. They are unobtrusive and were placed at this location so that the trucks leaving the main system have more than sufficient time to return to their normal freeway speed.

Weighing Subsystem

Size and number of scales - One 9-ft and three 3-ft platform scales, all 12 ft wide and centered in a 16-ft lane, comprise the weight sensing elements of the system. The narrower 3-ft platforms are located after the wider platform, respectively, on 10, 20, and 40-ft centers. The original purpose of these spacings was to cover the range of dynamic effects to be expected from vehicles traversing the system.

Load Cells - Axle load forces are sensed by strain gage load cells supporting the scale platforms at each of the four corners. The analog output signals from each cell are series-connected and the resultant signal is transmitted to the data collection and computing equipment. Load cells are individually excited, by floating power supplies, which provide 10 v.d.c. excitation to each load cell. Scale No. 1 is only half as sensitive as each of the other three scales. This is required due to the wider scale platform which may bear two or three axles simultaneously; the narrow scales will never bear more than one axle at a time. This reduction in sensitivity is accomplished by using half the signal amplification provided for in the other three platforms.

Weight Sampling - Whenever the scales are active, i.e., there is an axle in the system, the system multiplexer connects each scale output to the analog-to-digital (A/D) converter once every 1.2 milliseconds. The A/D output signals, with their scale identification, are then transmitted to the computer where they are stored until the scales become inactive, at which time an average weight is computed. If the number of samples from any scale exceeds 96, those taken after 96 are discarded. When vehicles are traveling at 5 mph or slower, the 9-ft scale (No. 1) is the only one seeing an axle long enough to be affected by this limitation.

Surface Switches - Tire-actuated switches at or near the tire-road interface are necessary to indicate when an axle is fully on the scale platform. These switch signals control the manner in which weight signals are handled by the rest of the system, and thus are critical. After experiencing difficulty and lengthy delay attempting to develop a strip-type switch embedded in the scale surface, the strip concept was abandoned and eight photoelectric switches were assembled and installed; one each at the leading and trailing edge of each scale platform.

With only minor problems, these switches provided satisfactory service during good weather. They were inoperative whenever the pavement was wet because water droplets would produce false tire or axle indications.

Dimensioning Subsystem

Width - The width measurement of the vehicle moving through the electronic scale system is accomplished by the interruption of up to 72 infrared light beams from sources in a pit, aimed at 72 detectors mounted on an overhead truss. The 36 right and 36 left detector signals are converted to a 12-bit gray code using integrated circuit logic components. This information is retained until after the vehicle passes through the system and is then input to the computer. The computer program utilizes a gray code equivalence table, where the distance from the platform center to each outermost interrupted detector is obtained; the sum of these two distances is the vehicle width.

Height - The height of a moving vehicle is measured by 13 vertically mounted infrared light sources and detectors which produce a horizontal light beam array. Light sources for this array are contained in two enclosures mounted to the left vertical member of the overhead truss and the detectors likewise are in two enclosures on the right vertical member of the truss. The 13 detector signals are converted to a 4-bit gray code and transferred to the computer. A height equivalence table is again used to determine the vehicle's height; depending upon the highest beam that was interrupted. The width and height detector systems were found to be so sensitive that mirrors, exhaust stacks, and protruding ropes were being included in the measurements. To overcome this unwanted sensitivity, the system was altered so that when a vehicle's steering axle interrupts the first photoswitch on the surface of Scale No. 4, the height and width beams are all reset. The spacing is such that whenever a vehicle's front axle reaches the scale switch, any mirrors or stacks are already through the arrays and are not included in the final measurement.

Width and height increments - The incremental distances between width beams vary from 6 in. apart for the first three beams from center, to 3 in. apart for the next four beams, to 1-in. intervals for the next 24 beams, to 3 in. for the next four, and finally, 1 in. for the next two. The furthest vertical beams are located 6 ft 2 in. from the center of the platform.

The beams for height detection are located from 6 ft to 13 ft 10 in. above the surface of the roadway. The lower eight detectors are spaced at 1-ft intervals and the upper five are at 2-in. intervals.

Length - The center 10 vertical width beams are also used to detect the front and rear of the vehicle as it rolls through the light array. From the time required to pass through the array and the average speed of the vehicle, determined by the computer, the length of the vehicle is calculated.

Axle Spacing - The computer program calculates the speed of each axle of a vehicle by the formula:

$$S_i = \frac{D_{(3-4)}}{T_{4i} - T_{3i}}$$

where:

S_i = speed of axle i
$D_{(3-4)}$ = distance between leaving edge of Scale Nos. 3 and 4
T_{4i} = event time of axle i leaving Scale No. 4
T_{3i} = event time of axle i leaving Scale No. 3

After the last axle of a vehicle crosses Scale No. 4, the computer determines the average vehicle speed from the individual axle speeds. The last axle is recognized by the computer by virtue of its counting each axle as it enters the system and then counting the axles again as they leave the system.

For each axle after the first, spacing is calculated between two adjacent axles by the formula:

$$d_i = S_i\ (T_{4i} - T_{3i})$$

where:

d_i = axle spacing between axle i and axle i + 1
S_i = axle speed
$T_{4i} - T_{3i}$ = event times of axle i and axle i + 1, respectively, crossing the leaving switch of Scale No. 4.

The computer then checks the vehicle for axle weight violation. If the axle spacing is less than 9 ft, this axle is classed as the second axle of a tandem pair. In this case, it adds the weights of this and the preceding axle, and checks for a tandem axle weight violation. The legal limits stored in the "Limits File" are such that one tandem pair may be greater than 26,000 lb but not over 32,000 lb and all other tandems must be less than 26,000 lb. Single axles are not to exceed 18,000 lb.

Computer Subsystem

Pre-Processor - The pre-processor transforms the data obtained from the weight, dimension, and vehicle sensing transducers into a form that can be input into the computer. Its elements are mounted in a 7-ft high cabinet in the shoulder enclosure on the north side of the scale area (Fig. 4).

These binary coded digital signals are amplified and transmitted over the 1,400-ft cable to the scalehouse where they are input to the computer through its input-output junction box. In the reverse direction, the pre-processor accepts control signals from the computer to coordinate operations and clear local storage of data.

Computer Hardware - The system computer is a Scientific Data Systems (now Xerox Data Systems) SDS 92 general purpose computer with input-output buffer and integral console. The machine cycle time is 1.75 micro-seconds. It has a core memory of 4,096 12-bit words, a basic 6-bit I/O channel with channel interface and two I/O interrupts. In addition, there is a junction box with a 12-bit extender providing: a) 3 groups of 24-bit parallel input, b) one 24-bit parallel output, c) eight single-bit sense line inputs, and d) two priority interrupts (Fig. 9).

Computer Software - The automatic weighing and dimensioning system software is a highly modular, self-contained programming system. The elements of the programming system may be classified in several ways. The system specifications are grouped logically by:

a) Input-Output Specifications - where all communications with the outside world are defined.

b) File Specifications - where the content and format of the various classes of data are defined at the benchmarks of their life in the computer.

c) Program Writeups - defining the functions of the various program modules of Group a; and as they manipulate the data in and out of the files defined in Group b.

The automatic system occupies nearly all of the 4,096 words of core memory. About three-fourths are required for programs; and the remainder for storage areas. The physical groupings may also be described functionally as follows:

d) The System Start-Up Process prepares the programs and files for system operation, clears the volatile files, and leads the weighmaster through the start-up sequence. This program is in the Magnetic Tape Output Buffer Locations; hence, it is eventually destroyed after having fulfilled its start-up functions.

e) The executive and I/O Group handles the "dialogue" between weighmaster and computer, with the EXEC subgroup attending to the control and sequencing of all major tasks performed by the system.

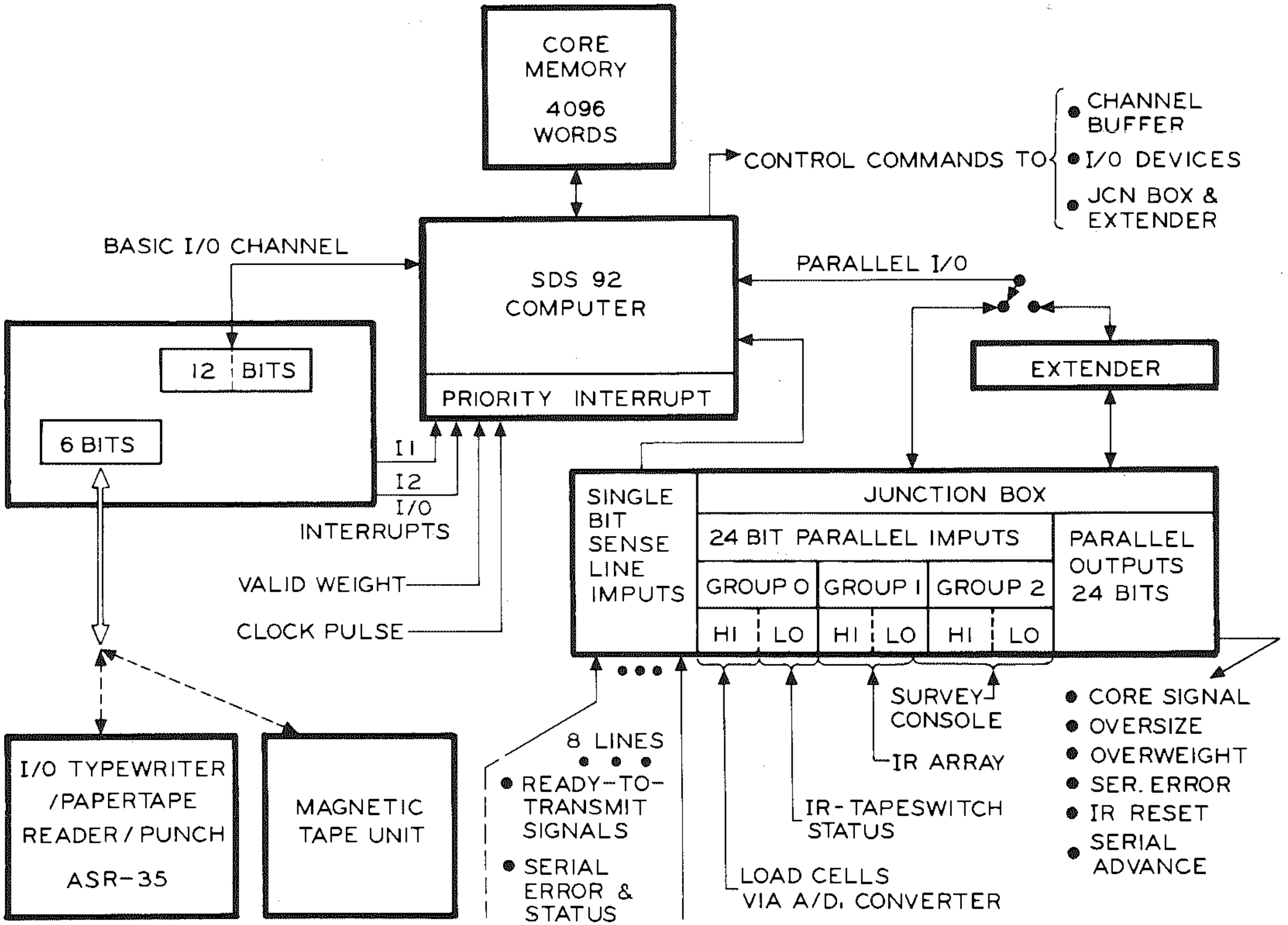


Figure 9. Scientific Data Systems computer system showing periferal equipment and I/O interface.

f) Certain General Subroutines (e.g., the Binary to BCD Conversion) are stored in the computer memory; the difference between subroutines and processes is not distinct, so an arbitrary definition has been made.

g) The Non-Volatile Files are tables of constants or lists of texts that are assembled with the programs, and do not change during normal operation.

h) The Volatile Files are those data storage areas that are in a state of constant change; the format of the data is maintained, but depending upon the file, and the level of activity, the contents of one of these files may completely change within a few milliseconds or remain stable for several minutes.

i) Scratch Pad Memory is a 31-cell portion of memory with two unique features: 1) instructions that access this area require only one memory cell for storage of the instruction, and 2) scratch pad memory accessing instructions require one less machine cycle for their execution than do full memory accessing instructions.

Functional Description - There are two principal computer options necessary to the operation of this system:

1) The junction box, with extender, permitting the computer to receive data from the electronic subsystems.

2) The system priority interrupts, telling the computer when to read data from the electronic subsystems. The system priority interrupts, in order of priority are:

a) Valid Weight Interrupt - generated when there is an axle on that scale and the weight sample has been converted to a 12-bit BCD number.

b) Clock Interrupt - generated by the Master Clock logic every 1.2 milliseconds.

When the system is inactive (i.e., no vehicles passing through the instrumented area) the computer cycles through the EXEC loop (Fig. 10) looking for tasks to be performed. Once every 1.2 milliseconds the clock interrupt is received by the computer, interrupting the program in progress and causing a branch to the Clock Interrupt Routine. This routine reads one word of status data through the junction box and stores this word in a small file area reserved for this purpose. The routine then branches back to the point of interrupt and continues with the normal instruction sequence.

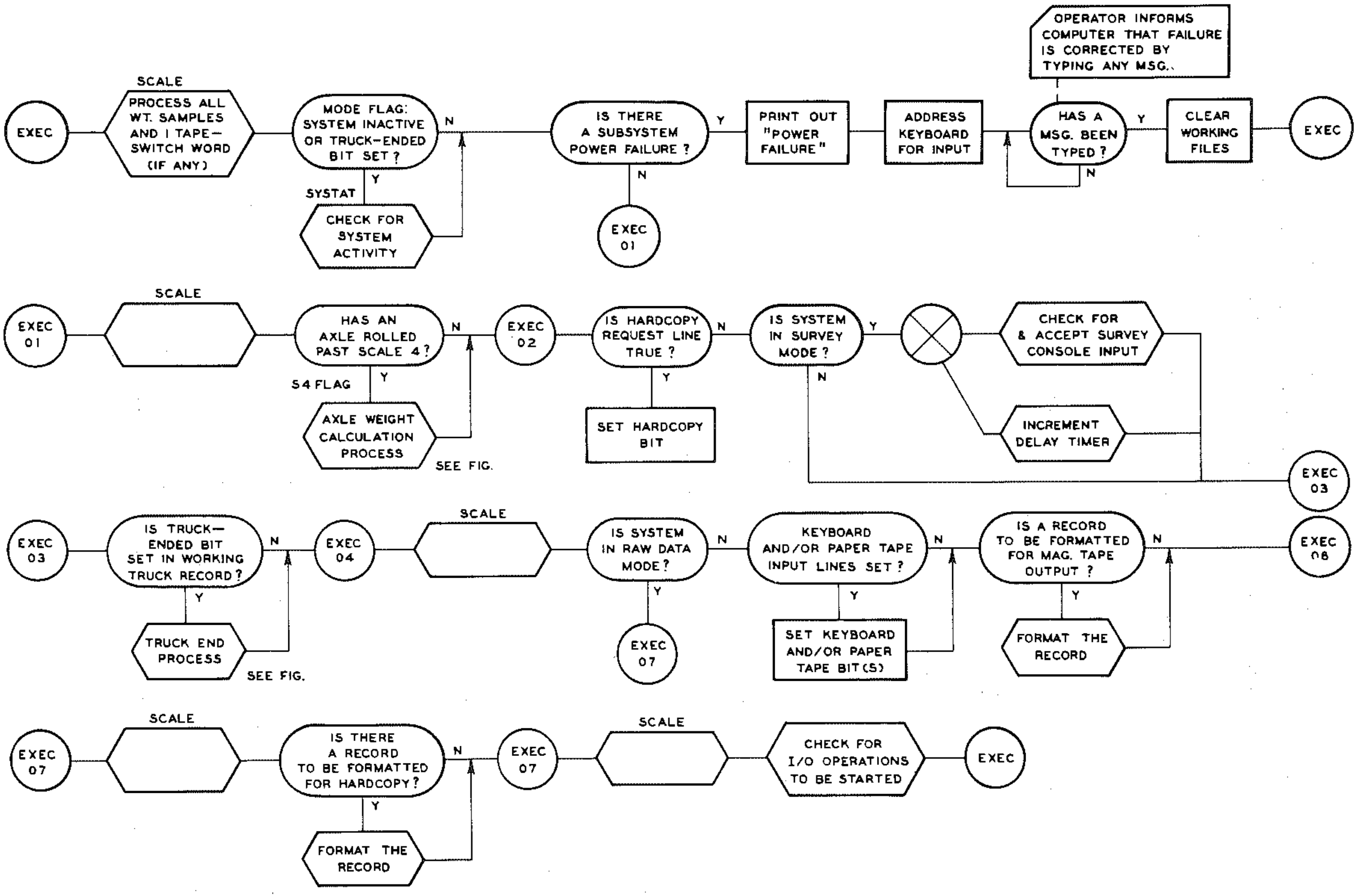


Figure 10. System program - EXEC subroutine.

Later, the Clock Process (with the Scale Process) called several times each cycle by the EXEC, finds that the Clock Interrupt has occurred. This process then updates the Internal Clock, a set of cells in which a count of the number of Clock Interrupts is maintained. The format is such that clock time is maintained to the nearest unit of 1.2 milliseconds, but also includes the year, month, day, hour, and minute. The data bits contained in the status word read in response to the Clock Interrupt are then examined. It is this word that tells the computer when a scale is occupied or when a vehicle is passing through the light array.

Now consider a vehicle entering the instrumented area. The first indication to the computer is a Valid Weight Interrupt, generated when the vehicle's steering axle has just rolled onto Scale No. 1, and the multiplexer has switched the input of the A/D converter to the output of the Scale No. 1 load cells. The computer responds to this interrupt in the same manner that it responded to the Clock Interrupt, except that the branch is made to the Scale Interrupt Routine. This routine reads the same status word that was read by the Clock Interrupt Routine, but, in addition, reads the weight sample output of the A/D converter. The two words of data are then stored in a pair of file areas. Then control is again returned to the program that was interrupted.

The Scale Process is called several times each EXEC cycle to check for Scale Interrupt data. When it finds that such an interrupt has been received and has "serviced" it, it: a) converts the A/D converter output from the 3-digit, 4-bit BCD form to binary, b) extracts the scale identification from the status word, and c) adds the binary sample to the summation for that scale, and increments the count of that scale's samples.

This sequence is continued until the Clock Process finds that a scale has changed from the active to the inactive state, implying that a wheel is about to roll off the scale. The Clock Process then picks up the sample sum and count from the Sample Sum Buffer, and moves the data to the 20-axle storage file. Those cells reserved for that scale in the Sample Sum Buffer are then cleared in preparation for the next axle to roll onto that scale.

When the EXEC finds that a new entry has been stored in the Scale No. 4 area of the 20-axle storage file, it "knows" that the axle has crossed each of the scales. Accordingly, it branches to the S4FLAG program. S4FLAG computes the average weight of the axle, and stores it in a working truck record (Fig. 11). The speed of the axle is also computed from the length of time that was required for the axle to traverse the known distance from the trailing edge switch of Scale No. 3 to the trailing edge switch of Scale

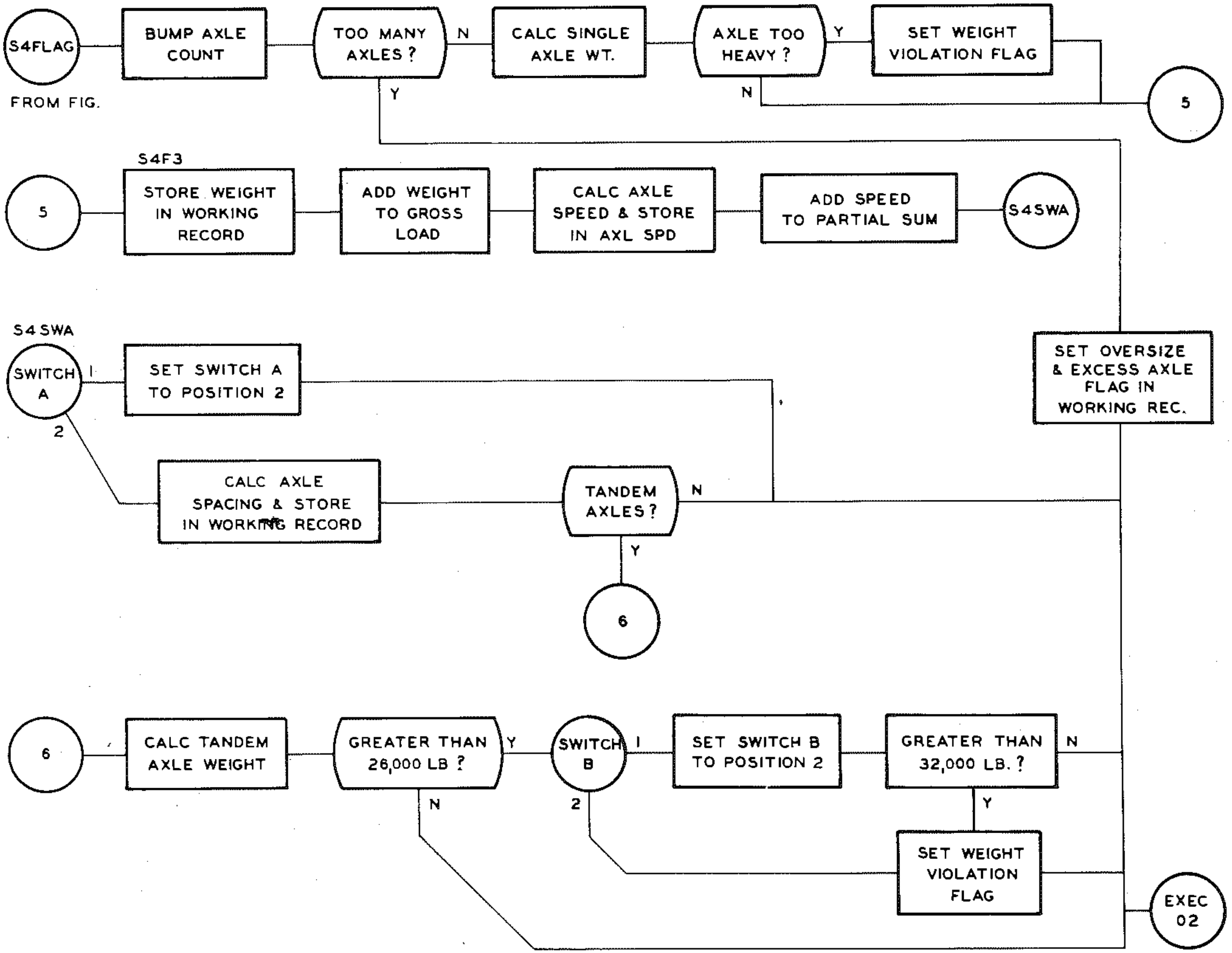


Figure 11. System program - S4FLAG determines resultant axle weights and legality of vehicle.

No. 4. (The Internal Clock time is stored in the 20-axle storage file when the sample sum and count is stored for a Scale No. 3 or Scale No. 4 axle passage.)

The Clock Process also checks for any changes in the center ten vertical beams of the infrared array (referred to as length beams). The program stores the Internal Clock Time of array interruption and array restoration from the previously computed axle speed and the total time of array interruption. A time estimate is made as to when the end of the vehicle should be just past Scale No. 4. When the Clock Process finds that the Internal Clock matches the time estimated for the end of the truck to pass Scale No. 4, the program sets a flag-bit in memory, declaring end-of-truck. The EXEC, finding this bit set, branches to the TRKEND process (Fig. 12), completing all of the processing required for the truck. It then moves the working record to a file containing space for eight historical records, checks for violations, and outputs signals that increment serial number counters and set violation alarms if required. TRKEND also leaves indications set if hard-copy or magnetic tape output is required, and prepares the system for the next vehicle. As long as 15 ft or more of space is maintained between vehicles, this system has no trouble segregating data for separate vehicles.

Operation Modes

Normal Mode - This is the mode of usual or "normal" operation. It is an operator-monitored, fully automatic operation for bypassing legal vehicles and sorting out and stopping the illegal vehicles--a normal weigh station operation effected as follows:

1) The gore signal switches are both in the "out" position so that all vehicles are directed into the bypass lane, except when the computer sets the signal to direct a violator to the scalehouse.

2) If the computer has detected a weight or dimension violation: a) the audible alarm sounds, b) the OVERSIZE and/or OVERWEIGHT button lights, c) the overhead gore signal directs the violator to the scalehouse lane, and d) the typewriter begins printing out a hard-copy record for the vehicle, containing the width, height, length, gross load, single axle weights, and spacings (Fig. 13).

3) To correctly respond to these outputs, the weighmaster should: a) turn off the audible alarm by pushing the SIG-OFF/RESUME button (Fig. 14), b) push the lighted OVERSIZE and/or OVERWEIGHT button after the violator

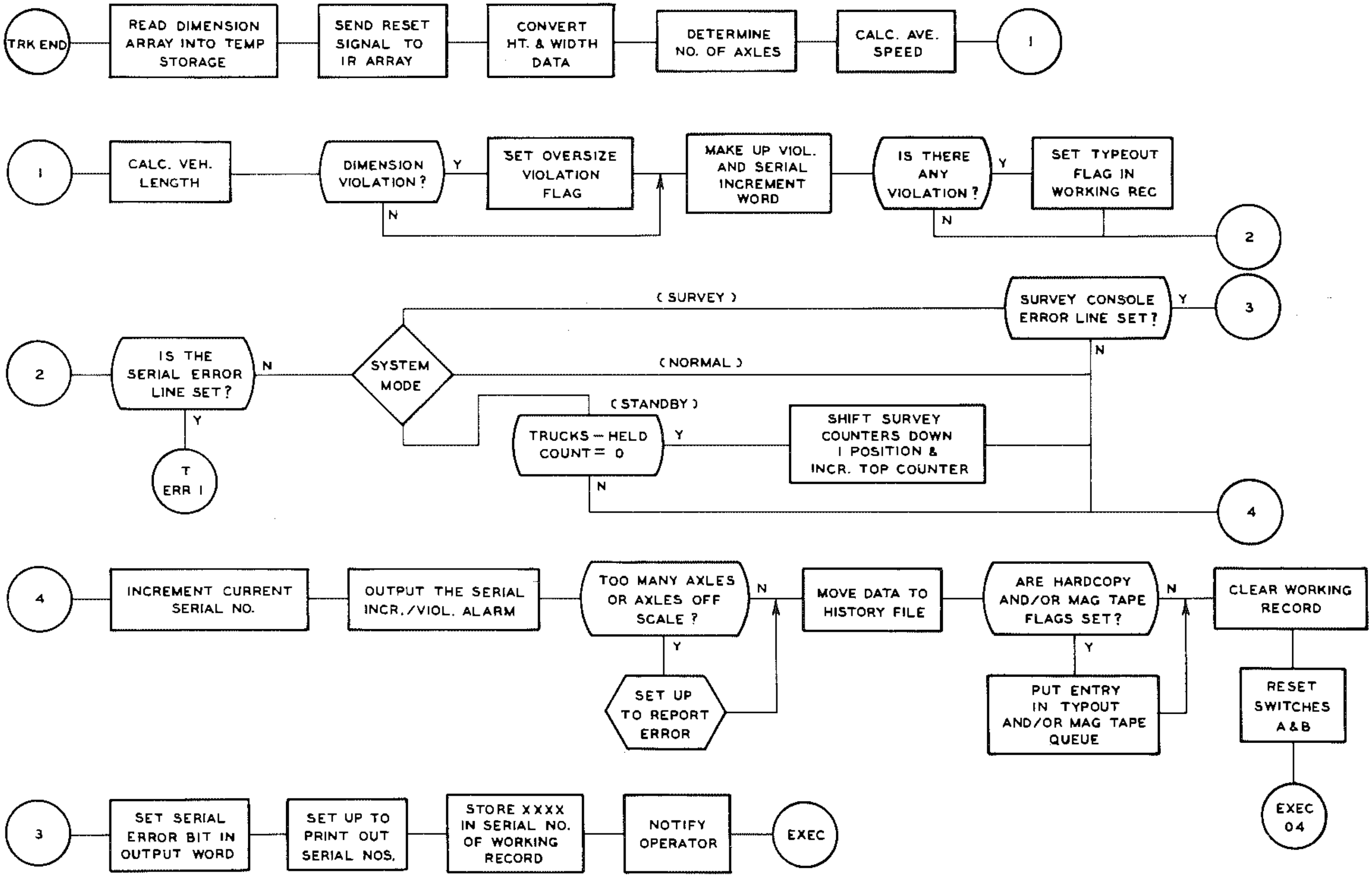
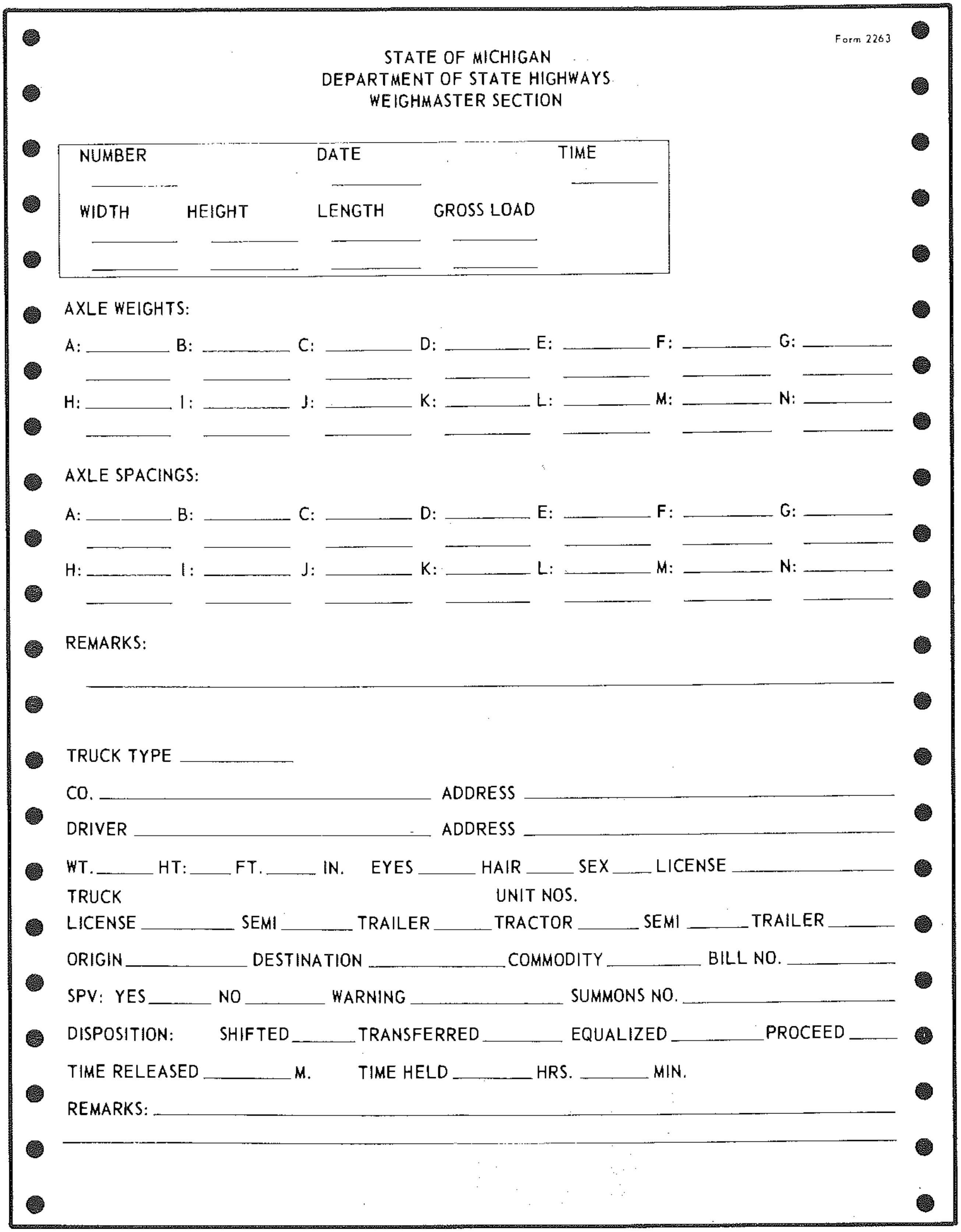


Figure 12. System program - TRKEND completes processing for each vehicle, up-dates history files, and types vehicle information.



Form 2263

STATE OF MICHIGAN
DEPARTMENT OF STATE HIGHWAYS
WEIGHMASTER SECTION

NUMBER ____ DATE ____ TIME ____

WIDTH ____ HEIGHT ____ LENGTH ____ GROSS LOAD ____

AXLE WEIGHTS:

A: ____ B: ____ C: ____ D: ____ E: ____ F: ____ G: ____

H: ____ I: ____ J: ____ K: ____ L: ____ M: ____ N: ____

AXLE SPACINGS:

A: ____ B: ____ C: ____ D: ____ E: ____ F: ____ G: ____

H: ____ I: ____ J: ____ K: ____ L: ____ M: ____ N: ____

REMARKS:

TRUCK TYPE ____

CO. ____ ADDRESS ____

DRIVER ____ ADDRESS ____

WT. ____ HT: ____ FT. ____ IN. EYES ____ HAIR ____ SEX ____ LICENSE ____

TRUCK LICENSE ____ SEMI ____ TRAILER ____ UNIT NOS. TRACTOR ____ SEMI ____ TRAILER ____

ORIGIN ____ DESTINATION ____ COMMODITY ____ BILL NO. ____

SPV: YES ____ NO ____ WARNING ____ SUMMONS NO. ____

DISPOSITION: SHIFTED ____ TRANSFERRED ____ EQUALIZED ____ PROCEED ____

TIME RELEASED ____ M. TIME HELD ____ HRS. ____ MIN.

REMARKS: ____

Figure 13. Vehicle data listing sheet. The upper portion is filled-in by the system, the lower portion is completed by the weighmaster.

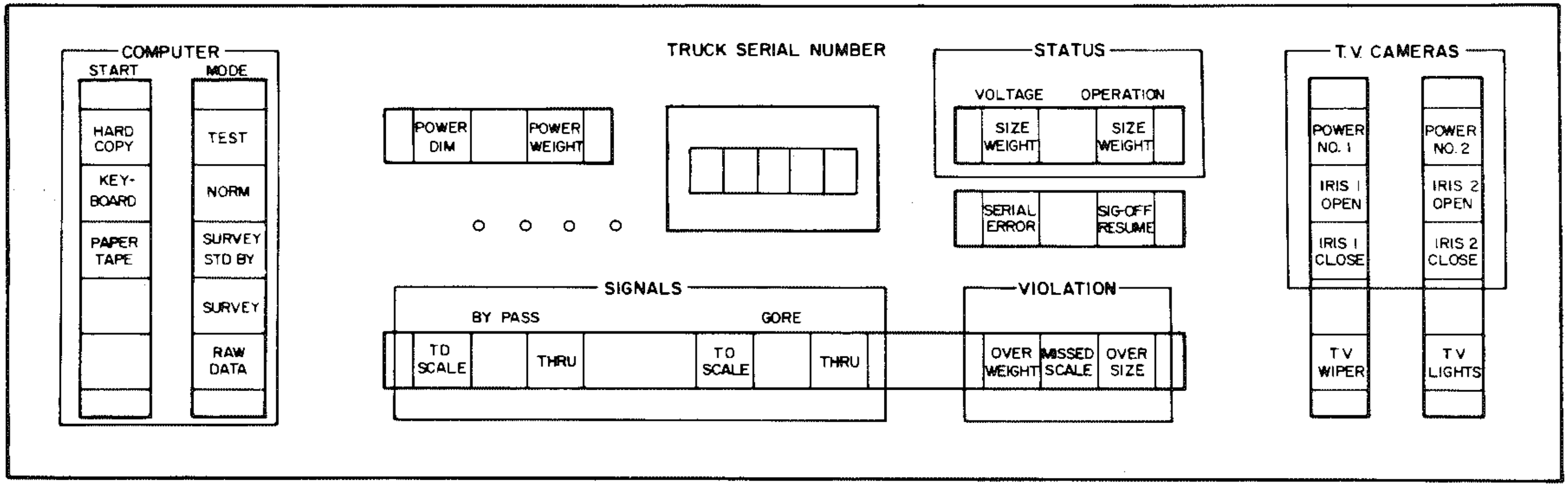


Figure 14. Control (weighmaster) console. System power, control, status, and vehicle status and control are performed from this console.

is committed to the scalehouse lane, to return the gore signal to the control of the computer (care must be exercised not to push this button when a following vehicle is too close to the gore, thus creating confusion in the mind of a driver as to which lane he should take), c) when the hard-copy form has been completed, tear off at the perforation and fill in additional information as required. This includes the static axle weights in the blanks below the computer entered values. Driver and vehicle information is entered only if a ticket is to be issued. (Some vehicles which appear to the automatic system to be in violation will be legal when measured statically).

4) To check the operation of the system: a) push HARD COPY button on the weighmaster console. This will cause a hard-copy record to be printed out for the next vehicle passing through the instrumented area, b) push the gore signal TO SCALEHOUSE button on the console to bring the next vehicle into the scalehouse lane, c) when the selected vehicle is committed to the scalehouse lane, switch the gore signal back to computer control. This vehicle may then be weighed or measured at the scalehouse and the results compared with the hard-copy. If desired, the hard-copy may be requested for more than one vehicle, but the HARD COPY button must be pushed after each vehicle rolls out of the instrumented area if hard-copy is wanted for the next truck (or the button may be held in for as many trucks as desired).

5) On occasion, the computer may declare a serial number error. This occurs when the Serial Number Counter does not agree with the serial number maintained in the computer's memory. When a serial error has been declared, the audible alarm sounds, and the SERIAL ERROR button is lighted. Release the alarm by pushing the SERIAL ERROR button, and then--holding the switch depressed--set the correct number into the Serial Number Counter by pushing one or more of the small buttons to the left of the counter (each button controls a single digit of the counter and a single push of a button advances the corresponding counter digit one unit). When the counter is corrected, push the SIG-OFF/RESUME button and release the SERIAL ERROR button.

Survey Mode - The Survey Mode is an expansion of the Normal Mode. To the vehicle traversing the system the operation appears identical, or "normal"; however, where the normal mode takes only vehicle measurements and weights, and only retains data on illegal vehicles (in the form of the hard-copy printout), the Survey Mode gathers more facts on the traversing vehicles and all data, whether from legal or illegal trucks, are recorded on magnetic tape.

During performance of this mode, the survey console is used by an operator who visually senses certain truck information, enters it in the console keyboard, and then transfers it to magnetic tape for later merging with the automatic measurements taken on that truck.

The system is switched to this mode by depressing the SURVEY switch on the control console. When the system is switched to this mode, the bottom serial number on the survey console will be one unit greater than the number on the control console. When the next vehicle leaves the instrumented area: a) the weighmaster console's serial number counter advances so that it matches the bottom number on the survey console, b) the Trucks-Held counter advances from zero to one, showing the number of vehicles that have rolled through the instrumented area but have not had survey data recorded for them. As more vehicles enter the system, each of the above actions occur. The serial number counter of the latest vehicle to leave the instrumented area is lit, as is the button beside it, and all of the serial number buttons below.

To input survey data for a vehicle, a) push one button in each data group on the survey console. More than one button may be pushed for the Spread-Tandem group only. If none of the data in a group apply to the vehicle being surveyed, push the "other" button in that group (the most efficient way to fill the board is to work from right to left), b) push the button beside the serial number assigned to that vehicle, and c) push the DATA TRANSFER button. If at least one switch has been pushed in each group, the DATA TRANSFER button lights, signifying that the computer will accept the data, d) after it accepts the data, the computer will release all the switches. Simultaneously the serial number for that vehicle will be removed from the survey console counters, all numbers above will drop to the next lower position as will the corresponding lights, and the Trucks-Held counter will drop back one unit.

It is important to note the serial number for each vehicle as it passes out of the instrumented area. During periods of high truck volume the television monitor will assist with this, since a vehicle will be in view at the time its serial number appears on the counter on the control console (directly below the monitor). It is expected that some errors may occur in this process, but every attempt should be made to input survey data with the correct serial number.

Serial Error conditions are much more likely in this mode than in the Normal Mode. To clear the error condition, release the audible alarm by pushing the SERIAL ERROR button on the control console. The serial error may be either in the control console counter, or in one or more of the survey console counters (or in both consoles). All of the counters, including the Trucks-Held count, must be checked against the serial number printout. When the error has been located and corrected, push the SIG-OFF/RESUME button to clear the serial error condition.

To collect magnetic tape records of processed trucks without the survey data: a) do not switch survey console on, b) operate gore signal under computer control (both switches pulled out as in Normal Mode), c) mount data collection tapes as in Survey Mode, d) switch into Survey Mode and type in a New Tape message.

Survey-Standby Mode - The Survey-Standby Mode is the transition stage between the Survey and Normal Modes. No new vehicles are added to the survey console (either to the Trucks-Held counter or to the Serial Counter lights). But, as long as the Trucks-Held count is not zero, survey data may be input as in the Survey Mode. Data may be input for a vehicle only when the button beside its serial number is lit.

When the Trucks-Held count goes to zero, the survey console shifts to a different manner of operation. Each time that the Serial Counter on the control console advances, all of the survey console serial counters advance as well (but the Trucks-Held count remains zero). This feature makes the Standby Mode a convenient transition state when going from Normal to Survey, since the serial number counters may be set up and the system operated in Standby until actually ready to go into survey operation.

The gore signals should be under computer control except when collecting survey data.

Raw Data Mode - This mode, again, is similar to the Normal Mode except that all vehicle data including every weight sample are recorded on magnetic tape during the passage of each vehicle through the instrumented area, and hard-copy is not printed out during the period that raw data are being written on tape. However, after a tape has been filled, and until the weighmaster types in a New Tape message, a hard-copy will be printed for violators, and the system will act in every respect like the Normal Mode.

While in Raw Data Mode, the gore signal may be operated under computer control. Violations will be signalled in the normal manner and the gore signal will be switched automatically to direct the violator to the scalehouse lane. The weighmaster will then weigh and/or dimension the suspected violator as usual, with the exception that there will be no hard-copy printout to which to refer.

If a serial error occurs, no serial number printout will be produced, so the weighmaster will have to either estimate the correct number or switch to Normal Mode in order to get a printout. The computer checks only for multiples of 10, so if the right-most digit of the serial number counter is 8 or 9, advance the counter digits to the next multiple of 10 and push the SIG-OFF/RESUME button. If this does not correct the situation, switch to the Normal Mode to get a printout.

Peripheral Equipment

1) Magnetic Tape Recorder. The tape transport operates at a speed of 75 inches per second and has packing density options of 556, and 200 characters per inch (556 characters per inch was selected as the most suitable for this system). The tape is 1/2-in. Mylar-base material, 1.5 mils thick. Tape reels contain up to 2,400 ft of tape. Characters are recorded on tape in seven parallel tracks. Six of the tracks contain information, the seventh track is a parity check.

2) Teletypewriter. The ASR-35 teletypewriter is the communication link between operator and computer. Its input/output typewriter is used for operator control, system start-up, error and status messages, and hard-copy printout. Its paper tape input/output unit is used to input test programs. One-inch wide paper tape is used, providing space for eight data holes and a sprocket hole in each frame of information; six hole positions for information, one for an odd parity check, and the eighth is unused. There are ten frames per inch of paper tape.

3) Weighmaster Console. The weighmaster console (Fig. 14) is located in the scalehouse near the weighmaster to facilitate his control of the system. Various control switches and indicators are located on the console face panel. Two separate control switches turn on the power for the dimension or weight subsystems. Controls are provided for operation of the television cameras. Status indicators alert the weighmaster to system malfunctions. An alarm buzzer with corresponding light indicator alerts the weighmaster to overweight, oversize, or missed-scale vehicles. A push-button switch silences the alarm. The gore signal controls permit the operator to bring vehicles to the scalehouse, or to bypass them back to the freeway, or if placed in automatic operation to bring only illegal vehicles to the scalehouse, bypassing all others. The signal in the scale bypass lane opposite the scalehouse can be activated to direct trucks in the bypass lane to return to the scalehouse. Computer-linked switches are also provided for any one of five modes of operation. They are: TEST, NORMAL, SURVEY STANDBY, SURVEY, and RAW DATA. A HARD COPY switch causes the

teletypewriter to produce a hard-copy printout for any legal vehicle. The system is programmed so that it normally only produces hard-copy printouts for illegal vehicles. The KEYBOARD switch allows commands to be input into the computer through the use of the keyboard. The PAPER TAPE switch allows computer commands to be input via paper tape. Finally, there is an indicator showing the serial number of the last truck electronically processed. Four pushbuttons to the left of the counter permit digit reset when desired.

4) Survey Console. The survey console (Fig. 15) is utilized when the system is operated in the Survey Mode. Each truck passing through the electronic scale system has its assigned serial number, weight, and dimensional data recorded on magnetic tape. The survey console permits the addition of other pertinent truck data to be manually entered onto magnetic tape against the same serial number assigned by the electronic system. The additional data are manually entered onto the survey console by a member of the survey team who observes the truck serial number and truck at the time of its first appearance on the weighmaster console and the closed-circuit TV. The survey console has two groups of switches or controls. The first group, the truck data set, provides the actual input codes to the computer. The second group are the console operating controls which enable the operator to turn on, set up initial conditions, transfer data, release without data, and adjust truck serial numbers on the counter if an error is detected by the built-in serial test circuit.

In addition to the truck data code, the console generates a command to the computer to read the data and a serial number test signal to check the real-time serial number. Upon receipt of data, the computer sends the console a data-received pulse, which restores all depressed switches to normal, advances the serial number of the unprocessed trucks, and deducts one count from the Trucks-Held counter. The computer supplies two additional signals to the survey console: the serial advance pulse, advancing the Trucks-Held counter or advancing the serial numbers if system is in Survey-Standby Mode; and serial error signal which provides a serial error light indication and resets the counter stepper relays to facilitate the correction of the error.

In the normal operation of the survey console, the operator sets up the starting conditions. These include turning on the power, phasing the mechanical registers by depressing the START button, and setting up the serial number of the trucks to be surveyed. The numbers will appear in ascending order with the lowest number at the bottom of the serial display. This lowest number will be for the first truck to be surveyed and will always be

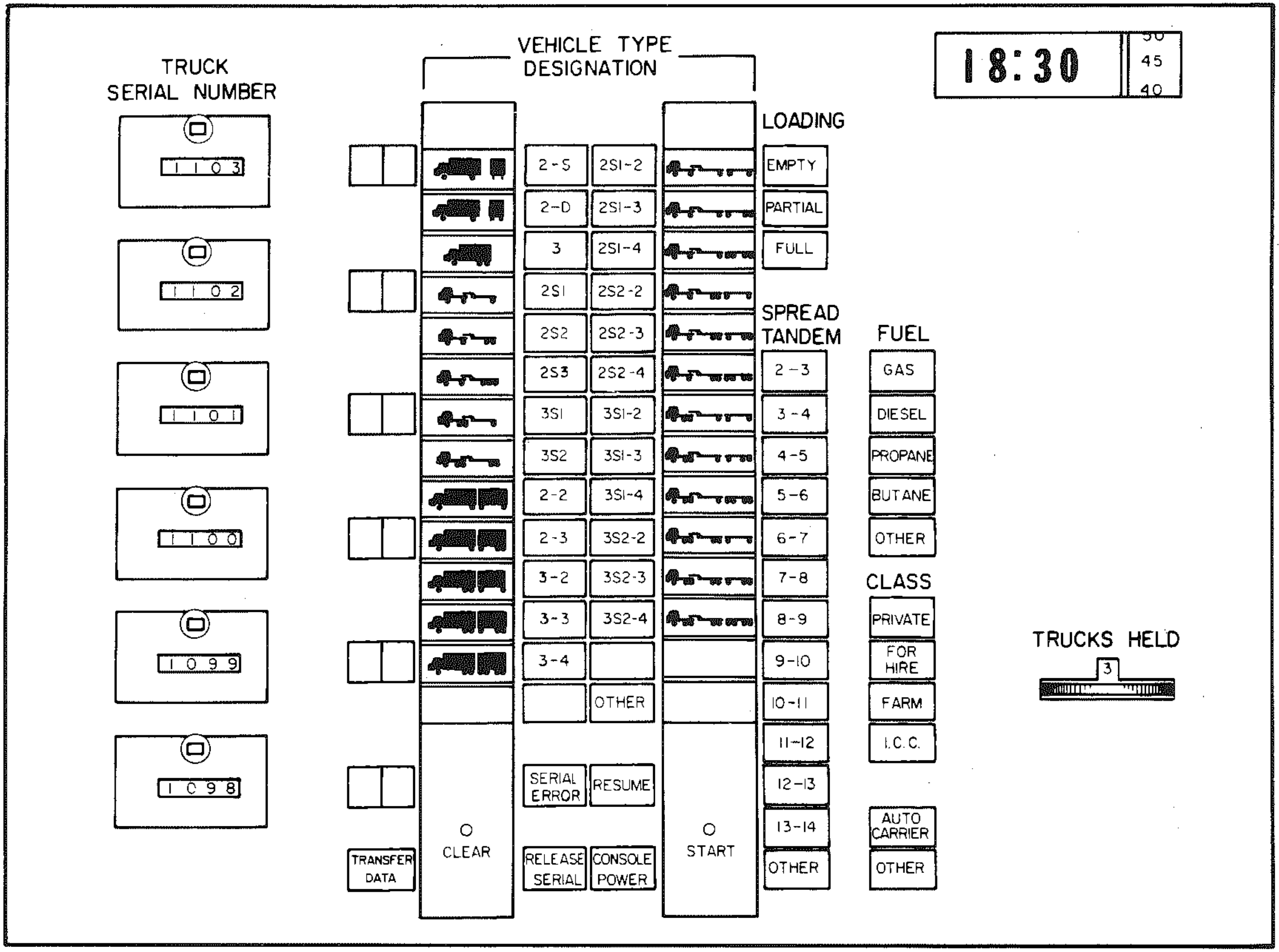


Figure 15. Survey console. Vehicle data indicated are set manually and transferred to computer memory for subsequent storage on magnetic tape together with weight and dimension data.

greater than that displayed on the weighmaster's console at the start of the survey, or one count greater if the survey is in progress but in the Standby Mode, with no trucks being held for processing. At the start of, or on the return to, the Survey condition, the first truck will cause the Trucks-Held counter to advance one count and the green counter will be illuminated. Each additional truck will add another step to the counter and cause the counter's corresponding green light to actuate, until the entire group is illuminated. Unprocessed trucks in excess of six will be counted, but their serial numbers will not be displayed. The survey console operator will manually enter data for each truck by starting with the data input switches at the lower right of the panel and progressively selecting the data switches until the TRUCK SERIAL NUMBER switch is depressed. Transfer of the data to the computer is then accomplished by depressing the TRANSFER DATA switch. The computer will read the code on this switch and then read the truck data switches and send out a data-received pulse releasing all switches and clearing the serial number of the processed truck. Under most conditions, this serial number is the one appearing at the window of the lower left counter. The clearing of this number will cause all numbers displayed to shift downward one step, and the top counter will increase by one count. If the truck processed is in the middle of the display, the clearing and shifting process will occur at that level and upward only, leaving the numbers below intact, awaiting processing.

5) Closed-Circuit Television Subsystem. A weatherproof housing with heaters, blowers, and windshield wipers, located atop a 26-ft pole, contains two Packard-Bell transistorized television cameras and the synchronizing circuitry that enables a split-field display of the scale area scene on a monitor mounted on the weighmaster's console. Although the split-field display requires only one video cable, an alternate cable is provided for independent operation of the cameras on separate monitors within the scalehouse. Independent power and iris controls are provided on the weighmaster's console.

6) Lighting. To provide for nighttime operation, five luminaire towers were installed. Two 400-watt mercury vapor lights were provided along the approach lane to the scales and three 1,500-watt quartz iodide floods illuminate the actual evaluation path. The poles for floodlighting, originally 50 to 60 ft high to conform to terrain, were reduced to 50 ft to facilitate servicing. Also, platforms for use during light adjustment periods were fabricated and mounted on the poles.

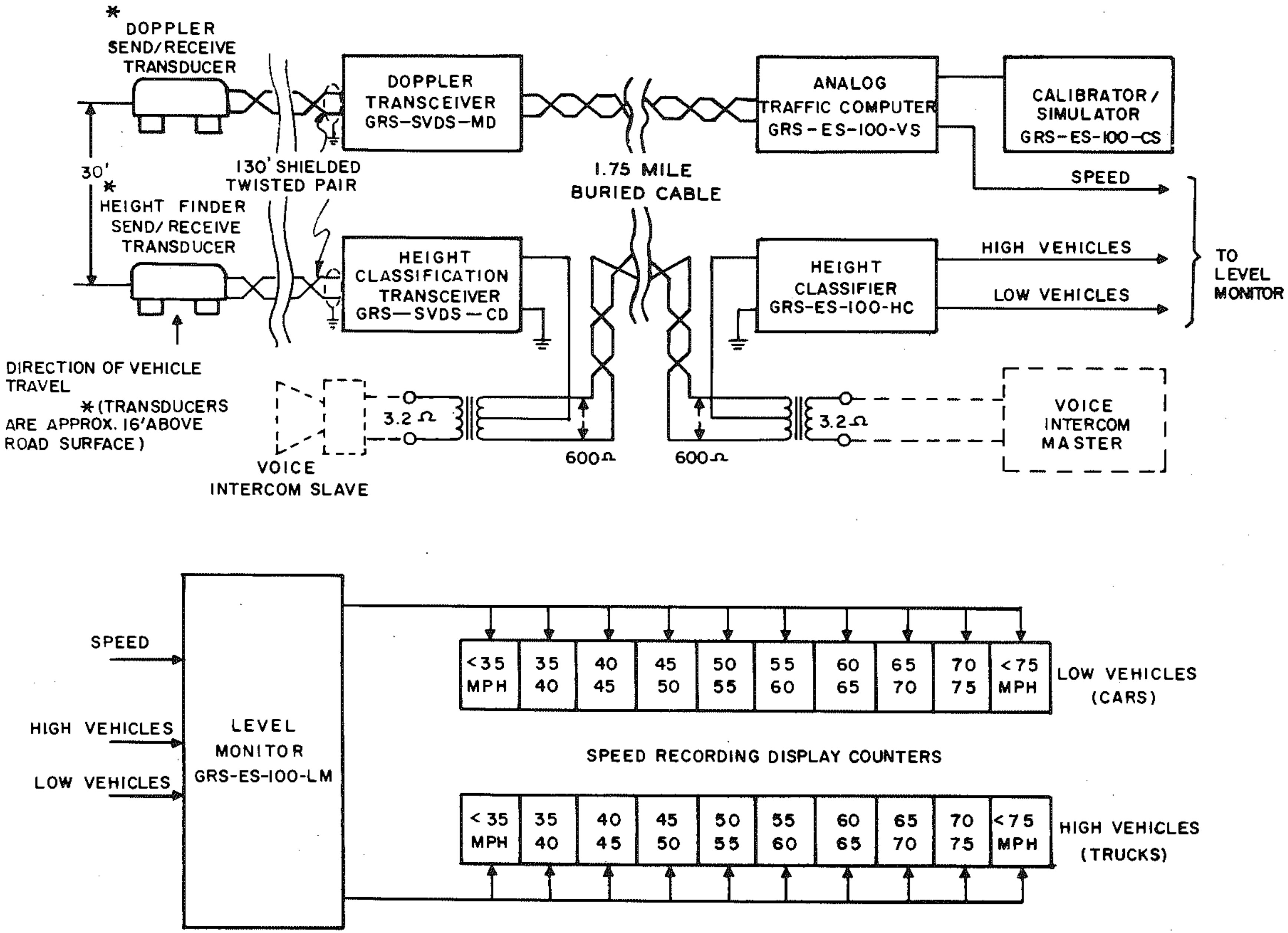


Figure 16. Vehicle speed and classification system.

Speed and Classification Subsystem

Reference to Figures 4 and 9 will show that while many components are shared between the weighing, dimensioning, and survey subsystems, the Speed and Classification Subsystem is entirely independent. Neither its sensors, transceiver, cables, nor console are in any way integrated with other subsystems. The equipment is made by General Railway Signal Co. and is the type used by traffic engineers for many years. It has known and proven capabilities and limitations (Fig. 16).

Both speed and classification are sensed by transducers mounted on the underside of the Mt. Hope Rd bridge which overpasses the I 94 traffic stream being studied. Two classification (height) transducers are mounted on the bottom flange of the fascia beam, one over each westbound lane, on the freeway approach side of the bridge. The speed transducers are also mounted over each westbound lane in a manner identical to the height transducers, but about 30 ft away on the leaving side of the bridge.

The reasons for locating the sensors 1.75 miles downstream from the scalehouse were twofold: to locate where in the traffic stream the trucks exiting from the scalehouse will regain normal highway speeds; and to use a bridge mounting, so that the sensors and transceivers would be inconspicuous and, therefore, not disturbing to drivers. The Mt. Hope Rd overpass, being the nearest downstream, was selected.

The purpose of this subsystem is to supplement the data taken at the weigh station; adding a total count of traffic by car, truck, and freeway speed. Thereby, when coupled with the detailed information from the other subsystems, providing the engineer with a complete picture of the traffic stream at the location in question.

Data recording is automatic, and counters can be read and reset at any time interval desired. Originally, it was intended to automatically record these data on magnetic tape along with weighing and dimensioning data for off-site processing. This plan was abandoned because of the high cost and because the principal interest in the experiment lay in the dynamic weighing and dimensioning of trucks.

Vehicle Classification - Vehicle classification (car or truck) as determined here is a function of vehicle height. It is sensed by pulse echo ranging transducers operating in conjunction with transceivers mounted nearby on the bridge abutment. The system is field adjusted to categorize vehicles as "high" or "low" with a 6.5 ft height as the separation point; i.e., any vehicle less than 6.5 ft high is defined as a car, and any over 6.5 ft as a truck. The validity of this separation height was confirmed by experimentation.

Vehicle Speed - Vehicle speed is measured by the bridge mounted transducers whose associated transceivers are also mounted on the bridge abutment. The system measures the Doppler shift of frequency of the reflected energy when a vehicle moves through the cone of ultrasonic energy radiating from the transducer. This unit, and also the classification unit, operate in the high sonic or low ultrasonic frequency range; about 18 KHz.

Console - Information from the detection site is transmitted 1.75 miles back through buried cables to the computing and recording console in the scalehouse. This vehicle speed and classification console contains analog computers which derive vehicle speed from the Doppler frequencies transmitted over the cables; and in conjunction with the height classifiers and level monitor, records speed information in two banks of electromechanical display counters (Fig. 16). One bank of counters records data from low vehicles, the other records data received from high vehicles. One of the ten counters in each bank records the total number of vehicles in that category. The remaining nine counters record vehicle speeds in ranges from below 40 mph to above 75 mph, in 5 mph increments. The eight classifiers receive data for their operation from the transmission cable driven by the height sensing units.

Timing circuits in the height classifier connect the speed output voltage to the level monitor for speed category classification. Suitable time is allowed for the level monitor to assume the correct classification before the count pulse is delivered through the level monitor relays to the display counter. The height classifier also (on the basis of the position of the high vehicle relay) routes the count pulse to the correct counter panel display.

Since two, height classifier-speed computer systems must share the same level monitor and counter display facility, circuits in the height classifier are provided to cause one system to wait until the other system has finished delivering its count.

III

SPECIAL PROBLEMS

This project was originally programmed for completion in July 1966, but because of the many unanticipated problems that occurred it was not totally completed and tested until February 1970. All system components and hardware were in place and ready for use, with one exception, at the end of the Philco-Ford contract in mid-1966. That one exception, the scale surface switches, was not a part of Philco-Ford's contract, so they bear no responsibility for the delays and problems caused by those units. In fact, it is appropriate to mention here that the part of the project performed by Philco-Ford was very excellently completed and none of the remarks made here or elsewhere in the report concerning problems are meant to reflect on the quality of their work.

The problem discussions that follow are presented so that those working on dynamic weighing and dimensioning systems for highway vehicles in the future will be forewarned and thereby able to avoid them.

Structural Problems

At the time Part A was programmed, it was intended that the breadboard aspect of the system would be confined to the electronic instrumentation, and the physical system of scale pits and platforms would be finalized for use in subsequent parts of the experiment. However, at the completion of Part A, Laboratory personnel concluded that Epsco, Inc., had done an excellent job with the breadboard electronics but that the physical system was very poor. It was thought that much of the poor system precision obtained could be attributed to physical system deficiencies; both weighing and dimensioning.

In the first installation of the four scales into the previously prepared pits, each platform consisted of two large I-beams with smaller I-beam stringers placed between and welded to the webs and upper flanges of the larger beams. For the large (9 by 12 ft) platform, the main beams were 21WF55 and eleven 12WF31 beams were used for stringers. The three small platforms (3 by 12 ft) each had five 18WF45 beams welded between two 21WF112 beams. Each of these assemblies was then covered with a 3/4-in. steel plate secured to the beams by intermittent welds along all joints.

Load cells were bolted to the underside of the outer flange of the large transverse beams at each end of the platform's four corners. The cells were mounted with their load buttons down and bearing on flat hardened plates secured to the top of each steel-capped concrete support pillar. These plates were secured after leveling the platform by placing shims between them and the support pillar cap plates.

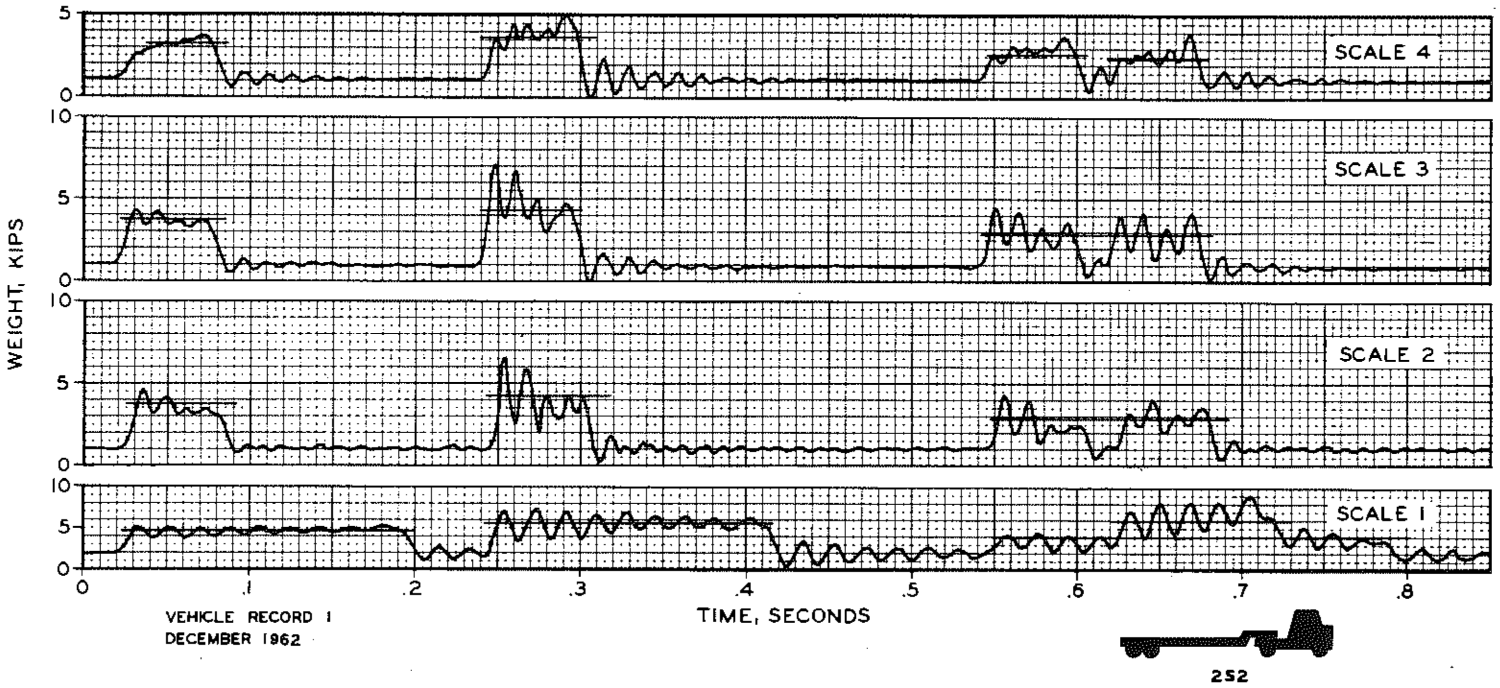


Figure 17. Analog platform signals showing platform oscillation during passage of a partially loaded vehicle. Horizontal lines indicate static weights.

An attempt to restrain the platforms in the longitudinal direction was made by inserting threaded anchors into both sides of the pit walls, drilling holes through the webs of the large transverse beams, and then inserting 1-in. diameter rods--threaded at both ends--through the web openings and into the anchors. These were then secured by tightening nuts on the rod ends opposite the anchors against the inner surface of the beam webs.

Obviously, tightening these bolts would place the platform and bolts in a tension condition which should prevent any appreciable movement in the longitudinal direction. This technique, however, produced side loading in the load cells due to forces resulting from vehicles accelerating or decelerating on the platform surface. The forces being resisted ranged from very low magnitudes for most vehicle axles to the order of 6,000 lb for a locked-wheel sliding tandem axle (assuming a maximum sliding friction coefficient of 0.20 between tires and steel platform surface, and a 32,000-lb tandem axle).

The platform assemblies received shop coats of paint at the time of their fabrication and the load cells were covered with a bituminous type seal coat. Wiring was run through grease filled conduit and the platform-to-pit joint was filled with a polysulphide sealant. This was the extent of anti-environment treatment.

These installations failed. Welds separated, tension rods loosened, platforms rocked on the cells, cells loosened and moved out of position, the steel concrete pillar caps were pounded loose, platform-to-pit joints failed and allowed salt water to stream in and the platforms became masses of red rust. Under dynamic loads the platforms exhibited large amplitude vibrations, and the weighing accuracies obtained with the system were erratic and, in general, very poor.

To confirm that adverse system precision was at least partially a result of the inferior physical system, a series of tests were performed at the site to determine exactly how the platforms were reacting when impacted by a dynamic load, and after load application. Platform motions were sensed by the load cells and by linear variable differential transformer type motion transducers. Signals were recorded on a high speed oscillograph with galvanometers whose response is essentially flat to 1,000 Hz (Fig. 17).

As a result of these tests it was found that platforms were moving in the horizontal plane as a unit and simultaneously vibrating at their structural resonant frequency in the vertical plane. These motions were combining in such a manner that the load cells under the platform corners were seeing an oscillatory applied load of approximately 60 Hz frequency, and of an amplitude often exceeding 50 percent of the applied axle load. Consequently, the load cell output signal that the electronic instrumentation was attempting to sample and convert to weight intelligence, consisted of this excessively oscillatory component super-imposed over the vehicle dynamic weight signal.

At the completion of these tests all data, together with system structural plans, were turned over to the Laboratory's Structures Group for analysis and recommendations on structural modifications to resolve the platform vibration problem.

Acting upon the resulting recommendations, a number of physical alterations were performed:

1) Diaphragm stiffeners were positioned and welded between the webs of the platform I-beam stringers.

2) Flange-to-flange stiffeners perpendicular to the web were added to the I-beams that bear on the load cells, in the area of bearing, to prevent motion of the flange with respect to the web, since the load cells are not positioned directly under the web.

3) High capacity springs (4,000 lb per in.) were procured, and spring mounts and anchors fabricated, for application of platform corner pre-loads (including platform dead loads) from 5,000 to 7,500 lb.

4) A system of transverse and longitudinal anchor rods was fabricated and installed so as to restrict platform movement in the horizontal plane.

5) The platforms were subsequently hot-dipped galvanized and coated with a petroleum base wax (Kencote-60). The concrete walls of the pits were painted with several coats of epoxy paint. After platform installation, a preformed polyurethane joint seal was inserted and a polysulfide surface seal was poured in place around the edges.

6) The load bearing columns under each platform corner, incorporating the load cells, were modified so as to provide vertical adjustment capability and to preclude the possibility of side loadings being applied to the cells (Fig. 18).

These modifications resulted in a significant reduction of the signal-distorting platform oscillations. Results of the accuracy tests are given in Part IV, "Data Analysis and Results."

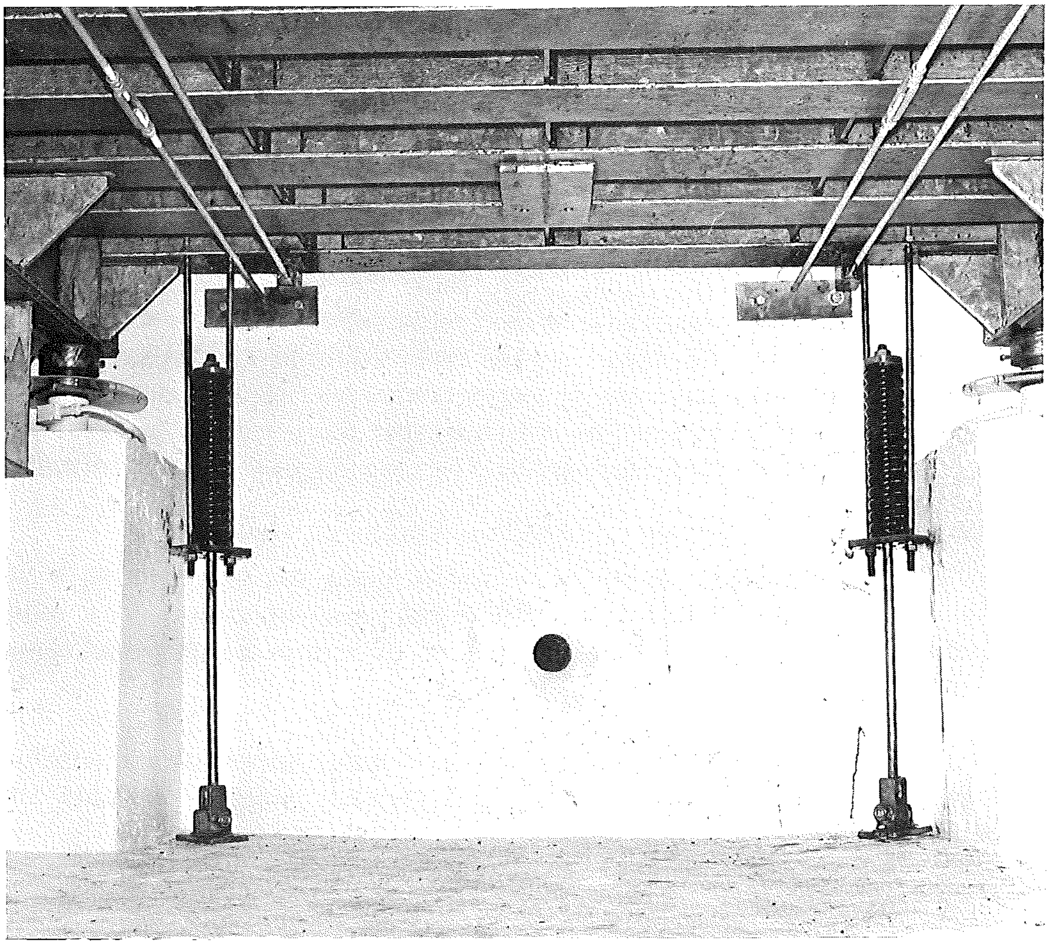


Figure 18. Interior of Scale No. 1 pit showing 4,000-lb/in. hold-down springs, transverse anchor rods, and load columns.

In the initial breadboard installation, electronic equipment was located inside the scale pits. Although careful precautions were observed during equipment installation, several component failures were directly attributable to the environment. Equipment was contaminated by moisture, chemicals, and dirt. Thus, during the rehabilitation of the platforms all electronic equipment was moved to the shoulder enclosure.

Dimensioning System Problems

The dimensional accuracy obtained by the infrared curtains of Part A was initially limited by the fact that the sensors were spaced at 3-in. intervals. In addition, height and width measurement were adversely affected by the fact that vehicle bounce, flapping tarps, etc., tend to bias height readings to the high side, and vehicle "crab," a common vehicle characteristic, tends to bias width readings to the high side. These tendencies are predictable, and for height and width were substantiated by the results of Part A. However, length measurements as determined in Part A were disappointing in that the method used in their determination would have been predicted to produce very good results. It consisted simply of summing the spacing between the extreme axles of a given vehicle and the front and rear overhangs of that vehicle. And, considering that axle spacing was the system's most accurate measurement, averaging about 75 percent of the total length measurement, the large errors that occurred suggested either an error in the computer program or length transducer problems. A study of these two possible error sources indicated that the computer program was correct, and thus, the trouble involved the transducers of the infrared system.

The detectors were cadmium selenide photo-resistors which have a worse-case response of 10 to 100 millisecond recovery time. As a result, data obtained from 104 vehicles showed an accurate length measurement was obtained only 4 percent of the time.

Infrared light source housings failed due to water penetration. Attempts to protect housings with gaskets, silicone grease, and plastic-filled cable entrance fittings were fruitless.

Physical mountings for the infrared components of the height measurement system were modified and re-installed in an attempt to determine the feasibility of establishing an operative curtain with beams on 1-in. centers as shown in the Appendix. Upon attempting to align the light sources and sensors, it was found that the light sources focused poorly and gave a very large, irregular shaped spot which impinged upon a number of sensors at one time, and was thus completely unsatisfactory. This dictated either modifying existing light sources or obtaining new ones. Before anything could be accomplished in this area, the proposals for Part B had been received and in each case the prospective contractor proposed complete re-engineering of the infrared system. Therefore, any intervening work by the Laboratory would probably have been of little or no value. As a result of this proposed re-engineering, FHWA personnel recommended that this portion of Post Part A be abandoned. That recommendation was accepted.

In Part B, the entire infrared dimensioning system was replaced. Light sources and detectors were mounted within sealed, steel enclosures with a glass front panel, and impinging sunlight on the detectors was minimized by the use of baffles protruding beyond the glass front (Fig. 19).

The photo-resistive detectors were replaced with photo-voltaic material having a response time of 10 micro-seconds. Heaters were used to keep the glass clear of snow and rain and to keep the interior dry. Source detector mountings were designed to facilitate their alignment. The performance of this improved system is discussed in Section V.

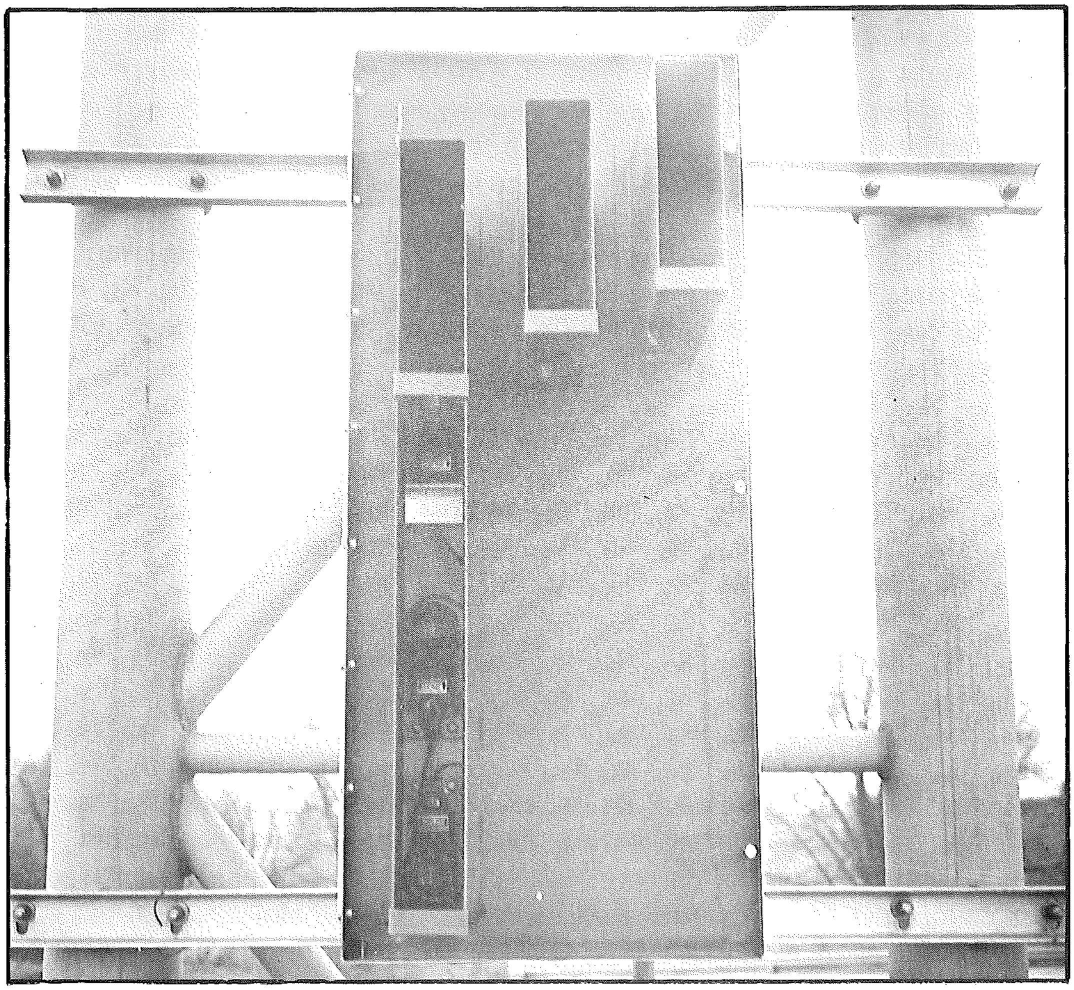


Figure 19. Height measurement infrared array. Note baffles.

Platform Surface Switch Problems

The two most serious problems encountered during this project, and those that were primarily responsible for the lengthy delay in its completion were: 1) the switches mounted on the surface of the scale platforms and, 2) numerous lightning strikes sustained and their resulting damage to the system electronics.

During the Part A phase of the project, a 5-ft long strip-type road switch was installed in each of eight milled slots on the platform surfaces. These switches were vital to system operation in that their openings and closures were used for starting the system, calculating vehicle velocity, measuring axle spacing, measuring vehicle length, and providing pulses to inform the computer that axle weight samples were valid, i.e., that an axle was fully on the scale. Unfortunately, this system component was a failure and despite a considerable amount of experimentation by Epsco a reliable switch, of reasonable life expectancy, was never provided. To perform the system operation and accuracy tests, it was necessary to use a short-lived type of switch taped to platform surfaces, not installed in the slots provided.

The reader should understand that the function of these switches requires a total performance device. Each of the eight switches must actuate and restore under each vehicle axle or the entire measurement chain for that vehicle is voided.

On an average day, the system will handle 1,200 to 1,500 trucks, each having from two to eleven axles. This means that a total of about 120,000 valid actuations and restorations are needed each day, or about 2,500,000 each month. Those familiar with electrical switches know that a mechanically actuated switch of this capability is not readily available.

In an attempt to resolve this problem, Laboratory personnel contacted the Tapeswitch Corp. (the only known manufacturer of long strip type switches) to obtain hermetically sealed switches, and the Laboratory's Materials Research Unit was requested to obtain the best embedding material available. Tapeswitches obtained were sealed in a supposedly moisture-proof neoprene tube. They were placed in the slots in each platform surface and a quantity of a polyurethane-rubber type joint sealant (designated PRC 3000) was poured around each switch; filling the slot until a slight positive meniscus above the surface was formed. In spite of these measures, moisture penetrated into the switch mechanism. Thus, some of the switches would not operate some of the time. Other designs and procedures were also tried but proved unsatisfactory. The slots in the platform were deepened in the hope of improving switch operation. An attempt was made to obtain a solid-state switch from a manufacturer of such devices, but delivery was not achieved due to failure to meet specifications. Other types of polyurethane materials were experimentally tested. Elevated temperature and vacuum curing of the various encapsulating materials were also unsuccessfully tried, and although some techniques were more successful than others, the switches could not be made to operate flawlessly for more than a few days.

Since the remainder of the system was operational, it was decided to replace the mechanical switches with photo-voltaic switches similar to those used in the dimensioning system.

In 1968, Laboratory personnel designed, built, and installed a complete photo-cell system which operated satisfactorily. Although aware of the limitations of this technique, due to snow and rain, it was decided to use this substitute system until another way could be found.

Lightning Strikes

No damage by lightning had occurred during the Part A phase of the project. This was probably due to the fact that no lighting towers had been installed for the electronic scale area, data transmission to the scalehouse was through cables placed above the ground, and the electronic components at the cable terminal were not susceptible to the effects of induced voltage surges. Consequently, when specifications were being considered for Part B, no special provisions were made for lightning protection other than the usual grounding practices.

The electronic scale area is exposed to lightning activity because it is slightly elevated above the surrounding countryside and barren of trees.

The first damage occurred shortly after completion of Part B, during the period of April 22 to May 5, 1966. A lightning bolt struck the aluminum case of a luminaire, burning a 1/2-in. diameter hole through the case at the impact point. From there, the charge traveled down the power line to an open circuit breaker, arced across the open contacts and also to a nearby control relay. From the relay, the charge dispersed through the system from the shields of the signal lines. The damage was extensive. Damaged components that were replaced included transistors, diodes, logic gates, resistors, capacitors, relays, three load cells, and the luminaire. Total damages amounted to approximately $10,000. As a result of this damage, the ground resistances of the various structures were measured with the help of the local power company. These resistances were not excessive but two 8-ft ground rods were added adjacent to each of the five luminaire towers, the television tower, the infrared truss, and the lane sign monotube. After placement, the sixteen rods were connected to their adjacent units with No. 1 bare copper wire. Then all units except the truss were connected to a 600-ft long buried No. 1 bare copper cable. Lighting and dimension relays were shielded to prevent arcing. Lightning arrestors were also added to the system.

On July 30, 1967, the contactor for both the quartz-iodide and mercury vapor lights was demolished by lightning. Only one of the system's lightning arrestors showed signs of arcing with probably the majority of the bolt surge taking a direct path to ground through the buried ground rods and cable.

The weighmaster's console was damaged by lightning twice during May and June of 1968. Damage also occurred many times in the parallel input-output sections of the computer. A pictorial description is presented in the Appendix.

In order to alleviate damage from lightning, all cables between light poles and television cameras were disconnected from the electronic section. Before leaving the site after test periods, the logic circuitry and weighmaster's console were disconnected from the inter-connecting cables between scalehouse and shoulder enclosure. Also, if the system was in operation at the time of an approaching electrical storm, the above disconnects were immediately made. These were temporary measures and are not a desired solution.

Contact problems developed due to the frequent disconnects. In an attempt to protect the computer input-output sections from voltages induced by ground currents, zener diodes were installed on the circuits. These diodes successfully prevented induced voltages of greater than 25v magnitude from damaging signal diodes on each data line.

Vehicle Oscillations

Vehicle axle loadings on a pavement fluctuate about the static weight while a vehicle is in motion. In order to obtain an estimate of the static weight under dynamic conditions, it is desirable to minimize vehicle oscillations.

Specifications for construction of the concrete pavement in the scale area were designed to provide for a smooth approach and passage of vehicles over the platforms. Subsequent to paving, relative pavement elevations were taken at 10-ft intervals longitudinally, and at 2-ft intervals transversely. The results indicated differences in elevation of 0.6 in. and 0.96 in., respectively. As a result, the pavement was removed. After construction of the new pavement, measurements were again taken; longitudinal elevations were within 0.48 in., and transverse elevations were within 0.36 in. Although not completely acceptable, this second attempt was a considerable improvement.

A continuous profile of the pavement was obtained through the use of the MDSHT-GM Rapid Travel Profilometer. The profiles obtained from the left and right wheel paths are shown in Figure 20.

Results from earlier studies at the Fowlerville scale site showed that vehicle oscillations are dependent upon axle suspension types, axle loads, and vehicle speed, with axle frequency being higher than body frequency. The oscillations result from roll, pitch, and bouncing of the vehicle. Body frequencies range from 1 to 15 Hz with a median of 4 Hz. Axle frequencies range from 3 to 24 Hz, with distinct bands centered at 3.5, 8.5, and 14 Hz.

As a result of these findings, and the irregularities in the pavement surface, the need for multiple scales was established.

Vandalism

During the course of the project several cases of vandalism occurred. Shortly after the system was placed in operation a forcible attempt was made to damage the computer. The computer, magnetic tape unit, and vehicle speed and classification system were located in an auxiliary room of the scalehouse. This room is normally locked and is not readily accessible. Evidence clearly indicated that a broom handle had been thrust repeatedly into the back panel wiring of the computer. Connector terminals were severly bent and wiring dislocated.

The second incident occurred a year later when the system was being prepared for further evaluation. This time an attempt was made to disable the magnetic tape drive by bending its guides out of alignment.

A third case of vandalism occurred over a weekend when no operator was on duty. The scalehouse was forcibly broken into and, although some money was stolen, no apparent harm to the electronic equipment was incurred.

As a result of these experiences, and interviews with concerned weighmasters and others, certain conclusions were arrived at.

In general, most of the prospective system operators believed electronic weighing to be beneficial to their work. There were, however, one or two people who felt that their positions were in jeopardy. They had apprehensions about the possibility of being replaced by a computer. Although attempts were made to acquaint operators with the function of the system, there was still reluctance to accept this new concept on the part of a few

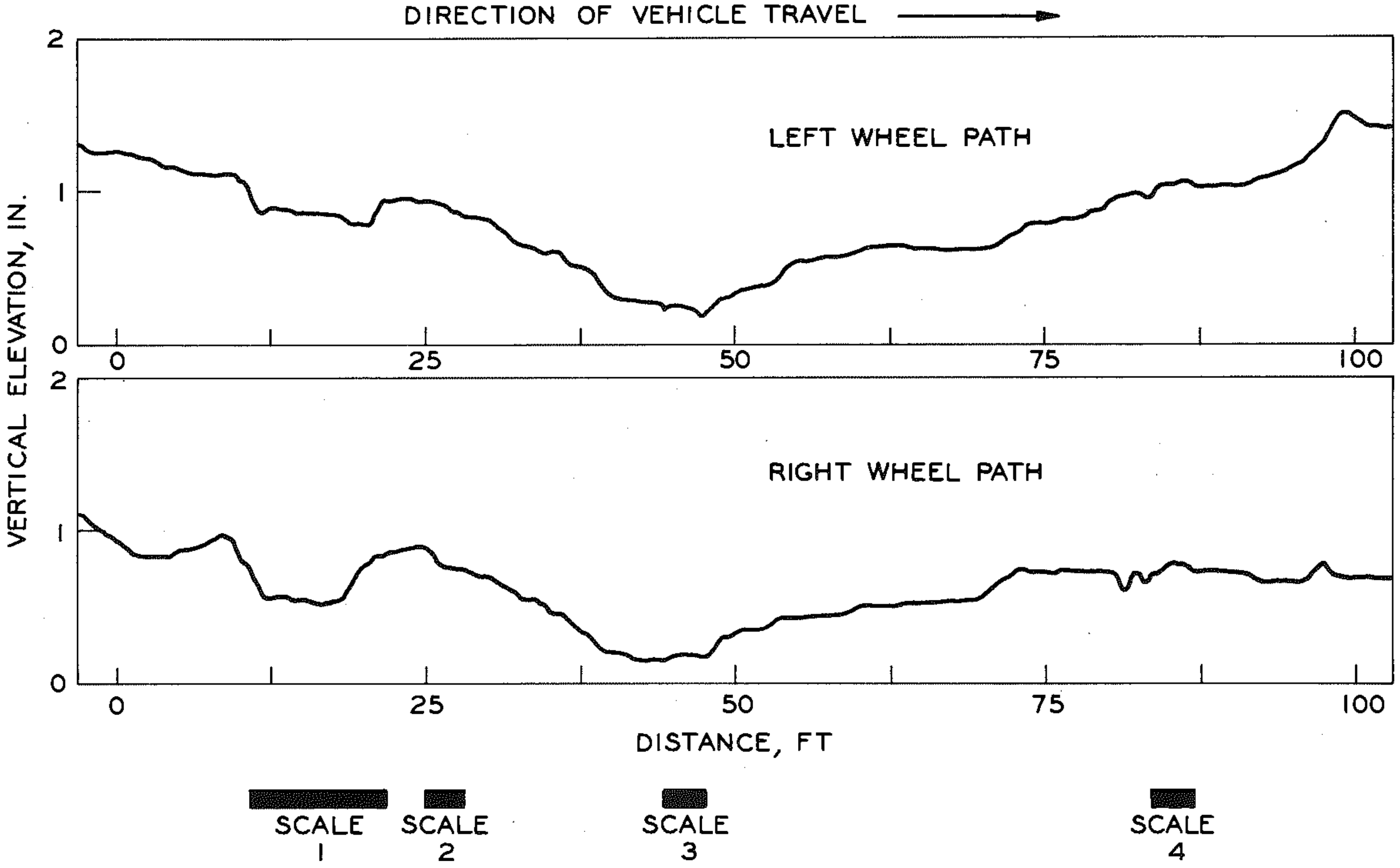


Figure 20. Pavement wheel path profiles showing location of scale platforms.

people. Because of these and other problems associated with the continuous operation of the system, it was never placed under the weighmaster's control.

Legal Measurement Limitations

The dimensional and weighing subsystems were not designed to determine all infractions of Michigan's Vehicle Code. In order to provide this capability, considerable further complications in system design would be required.

The legal length of vehicles is dependent upon vehicle type. The allowable length is also dependent upon the combination of truck-tractor, semitrailer, and trailer. These allowable combinations are also dependent upon the time of day and speed of vehicle. Since the system is not able to detect vehicle types, identification of these violations is impossible without operator intervention.

Also, under the provisions of the Michigan Vehicle Code, single axle loads cannot exceed 18,000 lb. Tandem axles are allowed 26,000 lb; however, one tandem axle can have 32,000 lb. If, however, the total vehicle weight does not exceed 73,280 lb, two 32,000-lb tandem axles are permitted.

Although these criteria could be determined, the computer program to perform tests for the provision were not implemented. Through computer programming, it was decided that the additional memory storage requirements and program complexity were not warranted.

Vehicles Stopping

During evaluation of the system, drivers would occasionally stop in the platform scale area; especially out-of-state drivers who were unfamiliar with the scale site. They mistakenly thought that the shoulder enclosure in the scale area was the weighmasters building. Although signs were placed indicating "DO NOT STOP," and "SCALE AREA AHEAD," they were ignored. This condition invalidated the system operation and also produced a hazard to closely following vehicles. On one occasion a steel hauler was forced to stop suddenly in the scale area, causing his load to shift, and driving the steel through the right side of the cab.

If vehicles, people, or any sort of activity were present in the scale area, there was a tendency for the vehicles to slow down or stop. It is our opinion that any unusual objects in the scale area will cause problems and every attempt should be made to minimize such objects.

IV

SYSTEM CALIBRATION AND MAINTENANCE

The subsystems requiring calibration were limited to the scale platform load cells and the separate Vehicle Speed and Classification system.

System maintenance, on the other hand, was required for all subsystems.

Scale Calibration

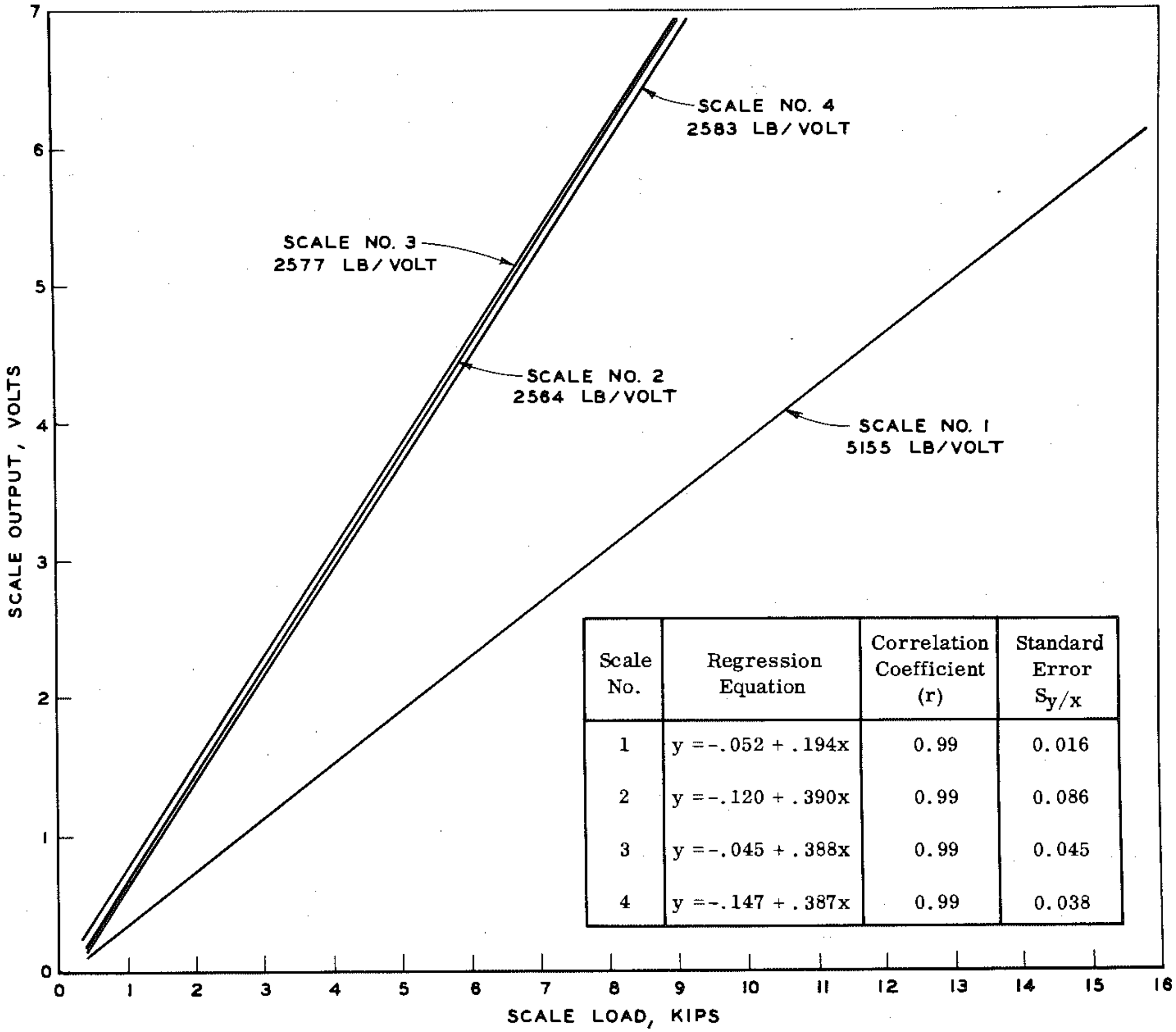
Mechanical Scale - Calibration of the mechanical scale is accomplished by placing precise 1,000-lb weights upon its surface and noting the difference in weighbar-indicated weight and that known to be on the scale. Each mechanical scale calibration performed during this study was carried out to 20,000 lb total load in 1,000-lb increments. Weighbar settings were recorded both during loading and unloading. In addition, the scale was checked for variation from off-center load placement by loading at the corners and along offset longitudinal and transverse lines.

The scale was found to be linear, with an error never exceeding 0.1 percent at loads up to and including, 20,000 lb.

Electronic Scales - The mechanical condition of the electronic scales was determined prior to each calibration. Longitudinal and transverse check rods were inspected for proper tension, hold-down springs for proper loading, and the entire platform was ascertained to be level and flush with the adjacent pavement. Only after all mechanical variables had been examined was the electronic calibration begun.

Four strain gage load cells support each scale platform. Each cell has its own power supply and the four cell outputs of each scale are series-connected to one amplifier; 16 power supplies and four amplifiers for the entire four-scale system. The 16 power supply outputs were adjusted with a digital voltmeter to an indicated accuracy of ± 0.005v.

The tare voltage output (from dead load) of each cell was then adjusted to 250μv. To insure that each cell was contributing equally, its balanced output was measured with the other three cells disabled. After balancing each of the four cells and then reactivating them all, the total four cell output equaled 1.0mv. This voltage was then amplified by a factor of 1,000 in the scale amplifier to give a tare voltage signal of 1.0v. The purpose of this tare voltage was to preclude the possibility of the scale signal going negative during platform vibration. Each scale was adjusted in this manner.



Scale No.	Regression Equation	Correlation Coefficient (r)	Standard Error $S_{y/x}$
1	$y = -.052 + .194x$	0.99	0.016
2	$y = -.120 + .390x$	0.99	0.086
3	$y = -.045 + .388x$	0.99	0.045
4	$y = -.147 + .387x$	0.99	0.038

Figure 21. Electronic scale calibrations (April 1965).

After completing all mechanical and electronic adjustments, the scales were each physically loaded in 1,000-lb increments to a maximum of 20,000 lb for each of the small scales and to 40,000 lb for the large scale. Scale amplifier outputs were taken with a recording digital voltmeter and later converted to lb/v for entry, as scale constants, into the computer.

No detectable non-linearity was found and the reliability of electronic scale operation is demonstrated by the scale calibrations listed in Table 2, representing a six-year period.

TABLE 2
ELECTRONIC SCALE CALIBRATIONS

Scale No.	Calibration Factors, lb/v				
	Dec. '64	Apr. '65	Feb. '66	Feb. '68*	June '70*
1	5,170	5,155	5,160	5,160	5,160
2	2,610	2,565	2,620	2,620	2,620
3	2,580	2,580	2,585	2,585	2,585
4	2,640	2,580	2,640	2,640	2,640

*Because of the demonstrated reliability of scale outputs, abridged tests were performed at these times with a series of known axle weight vehicles.

To complete calibration, the relationship between applied load and scale voltage output was determined by stopping axles on the electronic scale platforms, making precise recordings of the resulting scale output voltages, then statically weighing these axles on the mechanical scales. The resulting relationships are shown in Figure 21.

The test procedure consisted of selecting a vehicle as it approached the system, recording its normal-speed passage over the scales, and then stopping it at the mechanical scale for a very careful static weighing. Utilizing this procedure, some 140 single axles and a similar number of tandems were measured.

In addition to the tests just described, it was felt that the system's repetition ability should be evaluated. To this end, two Department trucks, one with a near legal limit single axle (16.25 kips) and the other with a near legal limit tandem axle (31.85 kips) each made 20 recorded runs across the scales at a controlled speed of approximately 35 mph. These repetitive passover tests showed zero percent error, with a 100 percent confidence level.

Electronic Scale Maintenance

Because of the extremely humid conditions experienced in below-ground pits of the type used here, it is necessary to clean and repaint them each year. Platform seals using polysulfide material became unbonded and were replaced with a two-component polyurethane material having a low durometer hardness.

The underside of the platforms were inspected monthly for physical deterioration. The condition of load cells, power supplies, amplifiers, and signal conditioning equipment were inspected daily. After energizing the system, the contents of certain computer memory locations were inspected to determine what tare voltage was present for each of the scales. If a malfunction existed in any of the platform electronics, these values would be abnormal.

Tire Switches

During the initial phases of the project, pressure-sensitive tire-actuated switches were used. Several times a day they required testing for proper operation. An indicator on the control console informed the operator when a switch was shorted. It was then necessary to determine which of the eight tape switches required replacement.

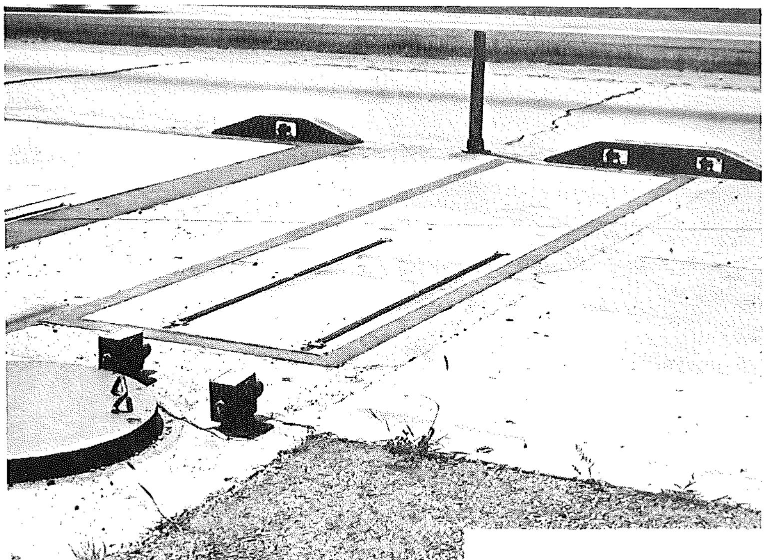
Vehicle data having large errors in the weight or axle spacing information were usually a sign of an open or shorted switch.

After the switches were replaced with photo-cell tire-actuated sensors, it was necessary to daily clean, and frequently adjust, the lenses (Fig. 22). This maintenance work was anticipated and usually required 30 minutes to complete.

After rainstorms, when the pavement had dried, they had to be again cleaned before the system could be made operational. This is obviously not a desirable condition, but it was the only alternative available without a major redesign of the system including additional computer memory.

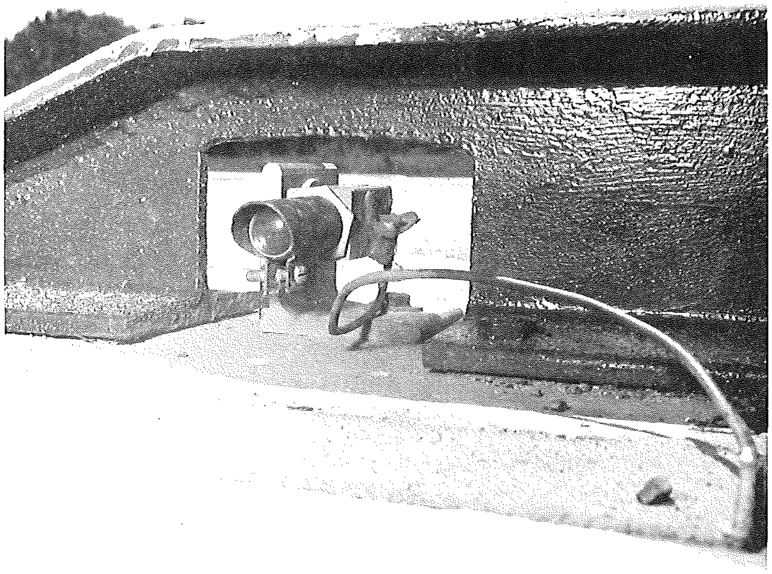
Dimensioning System

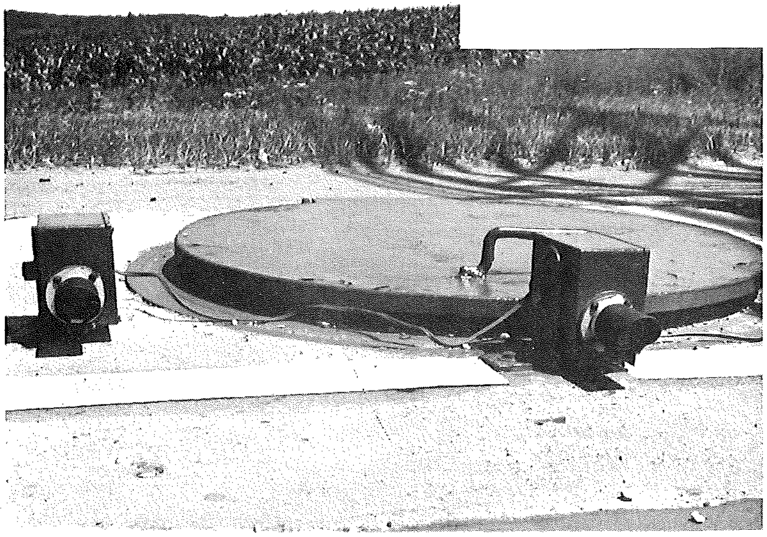
The dimension truss, although inspected periodically, has never required any maintenance. The pit containing the width array light sources contains an automatic dehumidifier and, since resolving the pit cover seal problem, the pit has required only occasional cleaning.



Mechanical tapeswitches on scale platform.

Photo-voltaic sensor.





Light sources with focused lenses.

Figure 22. Photo-cell tire switches used to replace mechanical tape switches.

Each of the truss-mounted light enclosures, which contain the above-ground light sources and detectors, has a glass panel between the unit and the outdoor environment. Dirt on these panels can affect light array functioning; therefore, they must be cleaned every three months. Other system elements requiring periodic cleaning are: the light port windows on the surface of the platform, pit-mounted light source bulbs and focusing lenses, detector assembly lenses in top and side-mounted enclosures, and light source bulbs and lenses in side-mounted enclosure.

Components of the light beam system will occasionally have to be replaced and their alignment should be checked periodically. Upon replacement of a sensor it is necessary to rebalance the light amplifier associated with the replaced sensor. Optimum adjustment from the infrared source through the lens in the pit cover window may be accomplished at night by placing a translucent piece of white paper over the window on the surface of the platform. The position and parts of the source assembly are adjusted to bring the lamp filament image into focus on the paper. When the combination of the sources and sensors are mechanically aligned and secured, the sensor output signal will be at an optimum level of 25 micro-amps or greater.

Computer and Peripheral Equipment

Maintenance of the computer subsystem has consisted mainly of replacing solid state devices damaged by lightning, aging, vandalism, or other causes. Cleaning and adjusting is routinely performed on the peripheral equipment; principally the teletypewriter and the magnetic tape recorder in accordance with the manufacturer's recommendations.

Site Maintenance

Pavement lane markings, plastic roadway delineators, and lamps in luminaires and computer controlled signs all require periodic maintenance or replacement.

Site snow removal was somewhat of a problem. When tape switches were used, they were occasionally torn or sheared by the blade of the snow plow. When the photo-cell system was used, only the approach was plowed. Snow in the scale area was removed by hand because of the obvious danger of damaging the exposed light sources and detectors.

In general, maintenance is not a serious problem. Physical site maintenance can be handled by on-site scalehouse personnel but an electronic technician familiar with the system should be available by phone for consultation or call to the site for repairs.

Calibration of Vehicle Speed and Classification System

The three basic types of data gathered by this subsystem are vehicle speed, vehicle classification, and vehicle count, the latter being divided into two categories--total vehicle lane count, and categorized vehicle count as a function of speed level and vehicle classification.

The components of the subsystem which require calibration are the speed measuring circuits and the classification circuits.

The Doppler circuits which measure speed consist of the ultrasonic sending and receiving transducers, the field transceiver, and the analog speed computer. It is possible to perform a fairly accurate calibration of the Doppler equipment by feeding a fixed audio calibrating signal from the simulator unit into the computer and adjusting a calibrating potentiometer for a nominally correct speed value on the speed indicating meter.

This approximate calibration method is based upon accurately presetting the transducer heads to a known radiation cone angle using a special angle measuring device provided by the General Railway Signal Co.

Variations in vehicle shape, and deviation from the center line of the lane, are uncontrollable factors that contribute statistical errors in speed measurement. However, better overall results were obtained by a further refinement of the calibration which consisted of comparing a sample of a few hundred Doppler measurements with independently measured vehicle speeds, and then modifying the calibration for best-fit with statistical sample.

The independent speed measurements were obtained by installing pressure sensitive switches 25 ft apart on the lane pavement in the area scanned by the Doppler transducer. The first switch was used to start a digital instrumentation counter, and the second switch to stop the same counter, thereby measuring the time elapsed while the steering axle of the actuating vehicle passed between the switches. Dividing the known switch separation of 25 ft by the elapsed time in seconds provided the vehicle speed in ft/sec.

Vehicle classification as either car or truck is performed by measuring vehicle height. Trucks were found to be above 6.5 ft in height, and cars to be below that height, if pickup trucks may be classified as cars, and passenger buses as trucks.

To calibrate the height detecting equipment, a knob with an adjustable scale skirt is mounted on the height transceiver chassis. This knob was initially set with its 6.5-ft scale mark opposite the index pointer, while reflecting ultrasonic pulses from a sheet of masonite supported 6.5 ft above the road surface on a car top. Although this equipment is provided with a thermistor compensator to minimize temperature sensitivity, it was found necessary to recalibrate the height transceiver during cold weather.

The resolution of the height measuring equipment, at the selected height, was found to be less than ± 0.1 ft about the selected value, using a special jig-mounted reflector constructed by Laboratory personnel. This jig made it possible to vary the height of the reflector very accurately and was used to recalibrate the height measuring equipment whenever desired.

Since the car and truck counts are stored in electro-mechanical wheel type counters according to speed level and car/truck classification, it was also necessary to calibrate the equipment in the scalehouse for the proper speed level discrimination. No further calibration is necessary for height classification, since the counts are routed to a high vehicle or low vehicle counter group through a single relay which is controlled in the height classifier by the classification detector for proper operation. The latter unit was previously calibrated with the adjustable height reflector, as described in the previous paragraph.

The routing of a vehicle count to the proper speed level counter in either the high vehicle or the low vehicle group is controlled by the level monitor, which is calibrated by properly setting ten front panel controls for the desired speed level limits, as indicated by the previously calibrated speed meter on the speed computer. This calibration is facilitated by the provision of a speed reference control which provides a continuously variable voltage to simulate the output voltage of the speed computer.

Operation and Maintenance - Results of data gathered are always immediately available and up-to-date, since the built-in analog computer functions continuously to convert data into recorded results whenever a vehicle passes under the transducers.

Information recording is permanent, even if power failure should occur, since the electro-mechanical display counters must be reset manually to clear accumulated counts.

Continuous, unattended operation of the equipment is practical, with manual intervention required only to transfer accumulated information to data sheets and to reset counters to zero at the end of each desired data accumulation period. Data may be accumulated for periods as long as a full week (168 hours of continuous operation) if desired. In a completely automatic system, data could be periodically transferred to magnetic tape at predetermined time intervals or upon demand by an operator's control.

Personnel requirements could be minimized by transmitting the raw data over a telephone line from the scalehouse, since the weighmaster on duty may be instructed to periodically transfer data from counters to data sheets. This eliminates the necessity for special trips to the transducer equipment location to reset counters, which would be necessary if recording were done at the transducer site.

No physical contact with vehicles in the traffic stream is required by the ultrasonic sensors used. Moreover, the transducers and their associated transceivers are unobtrusive, which contributes to realism in the data collected. Where speed measuring equipment is too obvious, drivers have a tendency to slow down, creating an unrealistic traffic flow situation.

Maintenance and upkeep of this type of equipment have been minimized through several years of operational experience, during which time reliability has been enhanced by frequent design improvements.

V

SYSTEM TESTS, ANALYSES, AND RESULTS

During the many years and phases of this project, scores of subsystem operation and accuracy evaluations have been performed. These studies had various purposes but generally were performed to direct activity towards system improvements or to detect and locate system faults or deficiencies. In some cases weight tests were performed statically with calibrated 1,000-lb weights or with special load-adjusted highway vehicles, but in most instances with selected vehicles from the traffic stream.

Subsequent to the repairs or changes necessitated by the many lightning strikes to the system, by system modifications, and by the many other problems encountered, recalibrations and accuracy determinations were performed. Checks on the accuracy of the vehicle dimensioning subsystem and the speed and classification subsystem were likewise frequently conducted during the course of the project. However, because these many recalibrations and checks were performed at widely varying times, on various system elements and subsystems and for varied reasons, their results are not included here. Instead, to bring the project to a logical and final conclusion a full-scale all-systems test was performed, and it is the results of these tests that are reported here, along with an analysis of these results.

The tests and analyses performed were not simply accuracy tests but were also aimed at determining those methods of processing the dynamic measurement signals that would provide superior static weight and dimension predictions. Further, they were to determine the effects on accuracy of vehicle speed, type, axle configuration, suspension, etc.; plus the optimum number and spacing of electronic scales.

Final System Evaluation

The final evaluation of the system was performed in two segments. The first, in July and August of 1968, consisted of a 1,000 vehicle sample. Hard-copy printouts, including all weights and dimensions were produced for each vehicle. Then static, mechanical scale weights were taken on each axle and all dimensions were manually measured.

Subsequent to the tests, it was learned that the leaving surface switch on Scale No. 4 was intermittently delaying closure after an axle had cleared the platform. Because of the intermittent nature of the problem and the impossibility of determining exactly when the malfunctions had occurred the accuracy of the entire weight sample was questionable. The dimension data, however, were deemed satisfactory and it is those data which are used here to evaluate the dimensioning system.

To fill the need for final weighing data, a second experiment was planned. It was determined prior to this second test that a 500 vehicle sample would provide statistically significant results. At this particular Michigan site, the mean number of axles per truck has been found to be approximately four. Therefore, the proposed sample would consist of approximately 2,000 dynamic axle weighings and a like number of static weighings. In order to obtain the electronic axle weights for each scale, the computer program was modified for these tests so that the average axle weight on each scale and vehicle speed were printed, rather than the usual four-scale average for each axle.

These tests were performed during February and March of 1970 and provided more meaningful data for the weighing precision analysis that follows shortly.

The survey mode equipment and the speed and classification subsystem were not evaluated during these final system tests. Both systems were evaluated many times during the life of the project and their operation is sufficiently straightforward that nothing further would be learned about them by additional tests. Therefore, only summary results are given here.

Weighing Precision

It is important that the reader be fully aware of the limitations of the in-motion weighing data analyses that follow. Use of the word accuracy has been avoided hereafter as this term suggests comparison with a primary or secondary standard and such is not the case in these tests. While it is true that the weight comparison standard (the mechanical scale) was very carefully calibrated many times during the project with weights which would qualify as secondary standards, this is not identical to weighing a truck axle.

It is true that the mechanical scale will very accurately report the weight it "sees," but that weight, when from a truck axle, can be varied by a number of factors. For example, consider the difficulty in weighing the second axle (normally the heaviest) of a simple two-axle truck. The weight reported from this simplest of weighings will be found different, and often significantly so, depending upon: whether the vehicle operator is holding his brake on, the friction in the vehicle suspension system coupled with the mode of entry onto the scale, the elevation of the scale platform with respect to the adjacent pavement sections, the elevation change (slope) of the adjacent pavement sections on which the axle not being weighed is situated, the length of spacing between the vehicle axles when the platform and adjacent pavements are not flush and dead flat, the engine speed of vehicles with air-bag suspensions and, quite certainly, other unrecognized factors as well.

Considering the above with respect to a simple two-axle vehicle aids one to understand the difficulties of static vehicle weighing. Now, however, extend that consideration to include large multi-axle vehicles of varying axle spacing and axle type, incorporating various suspension systems within one vehicle, with variably operating brakes on different axles, of sufficient load as to cause varying magnitude deflections of the scale approaches and of the scale itself.

The reader should now have a clearer idea of the problems of static weighing and recognize the even greater difficulties in evaluating an in-motion weighing system. Further complicating the evaluation is the fact that all of those static weighing difficulties apply equally well to dynamic weighing, plus the fact that a variably oscillating (roll, pitch, bounce) vehicle will seldom present its static weight to the underlying pavement, or to electronic scales set into that pavement even when running on a relatively flat surface.

To compound the problem, the pavement surface in the evaluation path of this particular project is exceptionally rough as can be seen in the wheel path profiles of Figure 20. Such roughness amplifies the already present vehicle oscillations and creates further problems in weighing precision.

To summarize all of the above, evaluating the performance of a system which weighs in-motion vehicles is a complex and difficult undertaking. Nevertheless, the reader should recognize that modern statistical techniques are of great value in establishing quantitative, defined relationships between variables such as are of concern here; and those are the processes that have been used.

Factors Influencing Precision

The work reported in this section is aimed at identifying and quantifying those factors degrading overall weighing precision. Then, knowing these relationships, and determining optimum correction coefficients, provisions could be included in the computer program to optimize precision.

Those factors suspected of influencing weighing results and consequently examined are:

1) axle weight magnitudes
2) individual scale accuracies
3) vehicle speed
4) vehicle class (axle configuration)

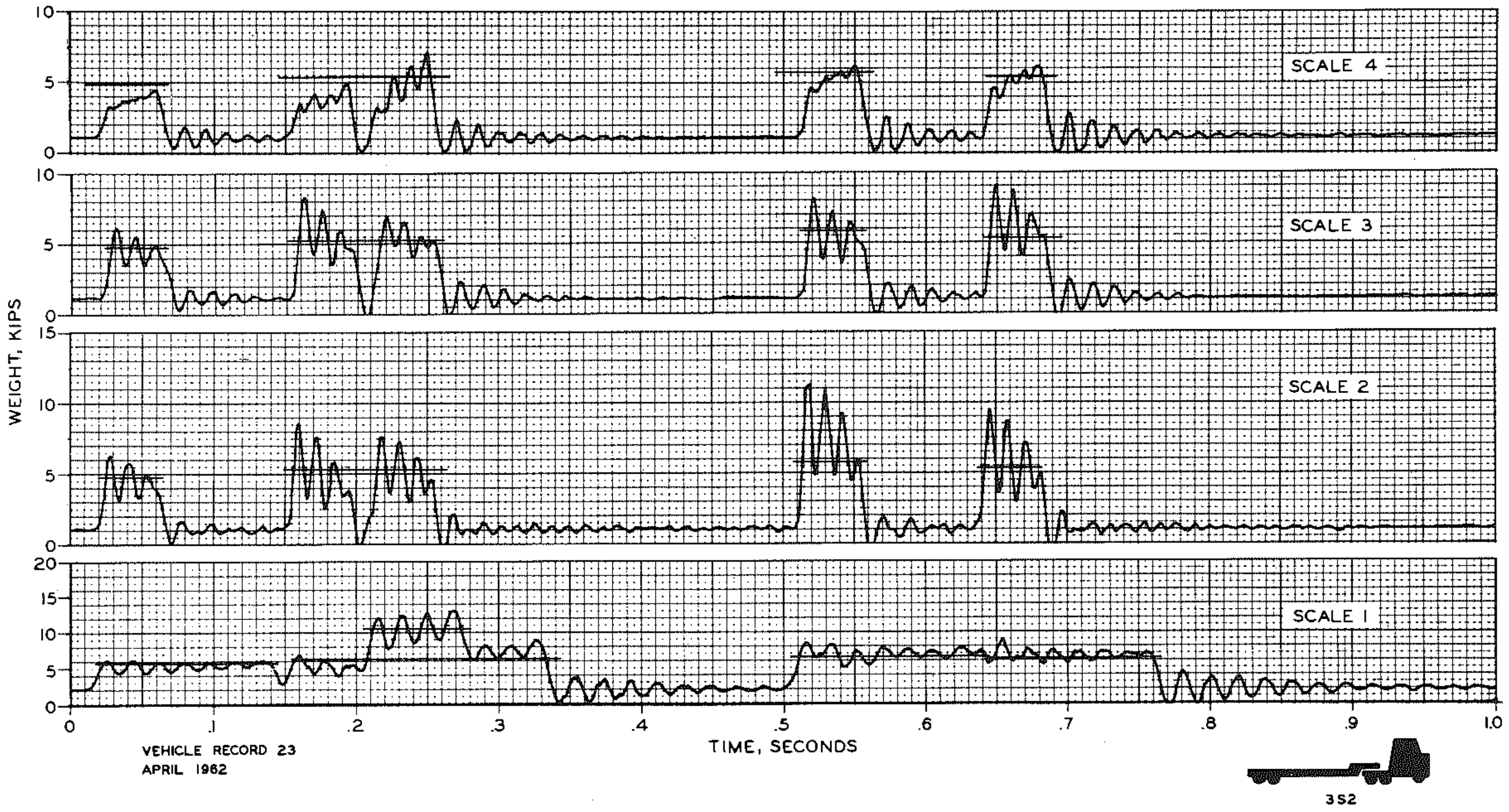


Figure 23. Typical analog weight signals from each of the four scales before rebuilding. Horizontal lines indicate static weights.

5) vehicle type (liquid, bulk, flat bed)
6) axle configuration (single, tandem, tridem)
7) axle suspension (leaf, coil, air, torque)
8) axle order and spacing.

Each of these factors are examined in the following text in order to determine their significance in optimizing weighing accuracies.

Weight Information

All weight information is contained in the four analog weight signals from each of the four platforms. Therefore, every attempt was made to insure that these signals were true representations of the axle weights.

In Part A, displacement transducers were used to record platform movement as vehicles passed over the platforms. These traces, together with analog load cell outputs and static weighings, showed an excessive amount of platform movement. The platforms were oscillating at their resonant frequencies. The amplitude of vibration was such that load cells were lifting from their bearing surfaces. Figure 23 shows typical platform load cell output signals (four cells combined) for a partially loaded vehicle. The resonant frequency of Scale No. 1 is about 50 Hz and 80 Hz for the other scales. But more important, the amplitudes of these oscillations are proportioned to the axle weight. In fact, they are almost equal to it. Thus, weight samples obtained from these signals would introduce even greater errors. As a result of these findings, obtained from a sample of 200 vehicles, a decision was made and approved to redesign the platforms as detailed in Section III.

Upon completion of this work, further testing was performed. Figure 24 shows the improved platform response to a loaded vehicle. The resonant frequency of Scale No. 1 was changed to 65 Hz and the other three scales to 100 Hz. There was also a considerable reduction in the amplitude of platform oscillation. Signal-to-platform noise ratios were now of the order of 15 to 1. This value does change, however, due to vehicle speed, and loading platform damping time increased slightly, but as can be seen from Figure 24 it is not significant.

One-Thousand Vehicle Weight Sample

During the final evaluation of the system 1,000 vehicles were electronically weighed. Trucks were randomly diverted from the traffic stream and passed through the electronic weighing and dimensioning systems. Vehicle

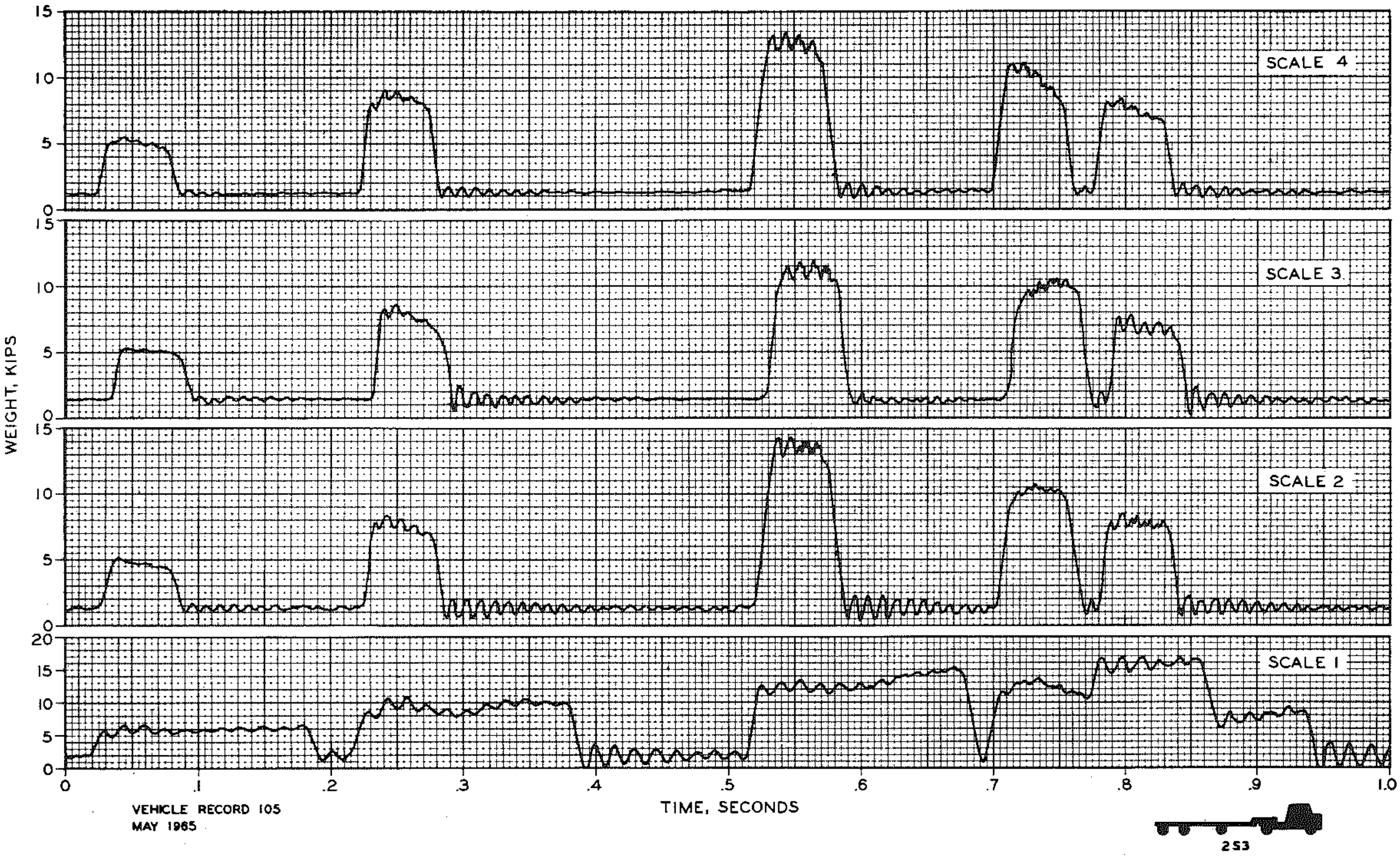


Figure 24. Typical analog weight signals from each scale after addition of transverse anchor rods and hold-down springs.

speeds ranged from 5 to 50 mph depending upon the driver and his familiarity with the scale site. Each vehicle was then directed to the mechanical scale platform where each single, tandem, or tridem axle was weighed and the data recorded.

This study resulted in the measurement of over 3,000 axles from all vehicle categories. The scatter plot in Figure 25 shows the precision obtained for the four scale average of each axle. Although a complete analysis of the data was performed, it is not included in this report for the following reason.

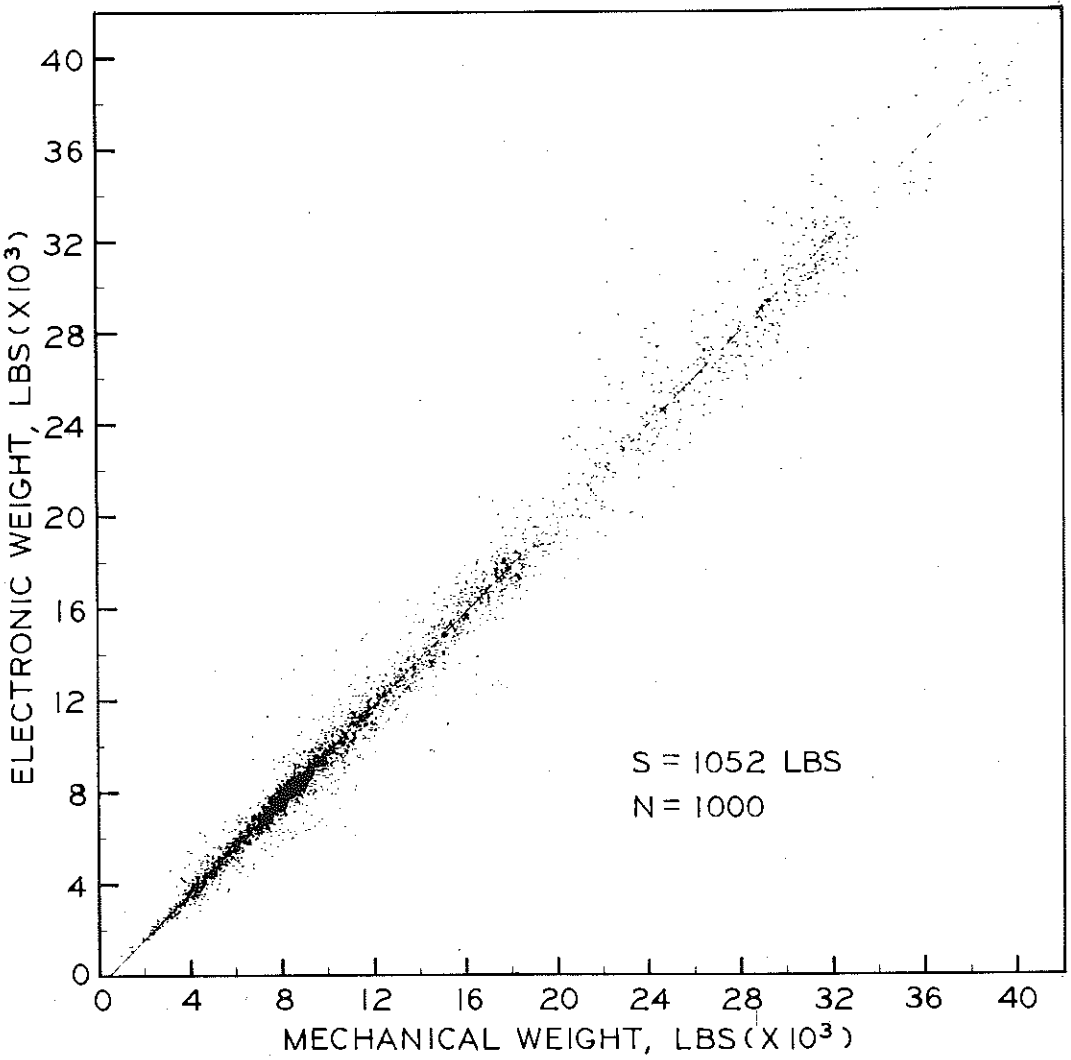


Figure 25. Scatter plot of weighing precision using four scales - switches malfunctioning.

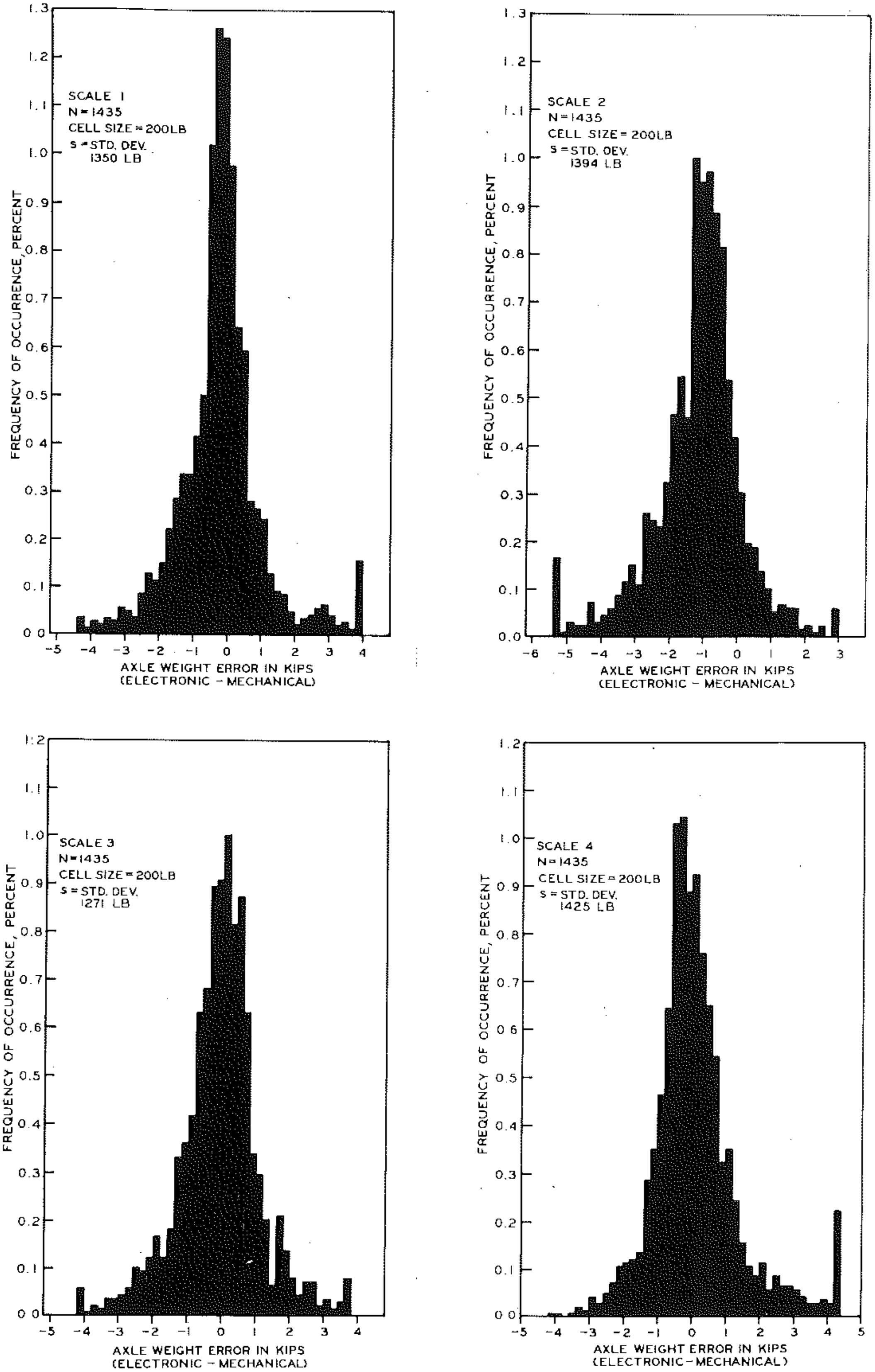


Figure 26. Axle weight histograms for Scale Nos. 1 through 4.

During the latter part of the 1,000 vehicle sample, the system was placed in the Raw Data Mode. In this mode, every weight sample is recorded on magnetic tape for off-line analysis. When these data were examined, it revealed that occasionally one of the trailing photocell switches was not responding properly. As a result, weight samples were being taken while an axle was leaving the platform. Therefore, average axle weights for that platform tended to be lower than the mechanical weights.

Five-Hundred Vehicle Sample

Because of the aforementioned problem, a subsequent 500 vehicle sample was taken. The following analysis is given from these data. Figure 26 shows the error histogram for each of the four scales.

Figure 27 is a scatter plot of the four scale average for each of the 1,435 axles. One standard error of 1,052 lb was reduced to 682 lb for individual axle weights. Again it is emphasized that this error is based upon the assumption that the mechanical scales are absolute; while in fact we know they are not.

To improve system precision, individual scale weighting coefficients were computed on the basis of this large number of axles. Using the coefficients so determined, individual axle weights may be predicted on the basis of the electronic scale outputs. This constitutes a "multiple regression" and requires solution of an equation of the form:

$$y = aX_1 + bX_2 + cX_3 + dX_4 + e$$

where, "$X_1 \ldots X_4$" represent electronic weights for an axle on Scale Nos. 1 through 4, respectively. Coefficients "a" through "d" control the contribution or weighting of each platform to the final reported weight. The constant "e" corrects for any bias in the combined scale readings. The computed coefficients are as follows:

$a = 0.243$
$b = 0.299$
$c = 0.234$
$d = 0.226$
$e = 347$ lb

resulting in the multiple regression equation:

$$y = 0.243X_1 + 0.299X_2 + 0.234X_3 + 0.226X_4 + 347$$

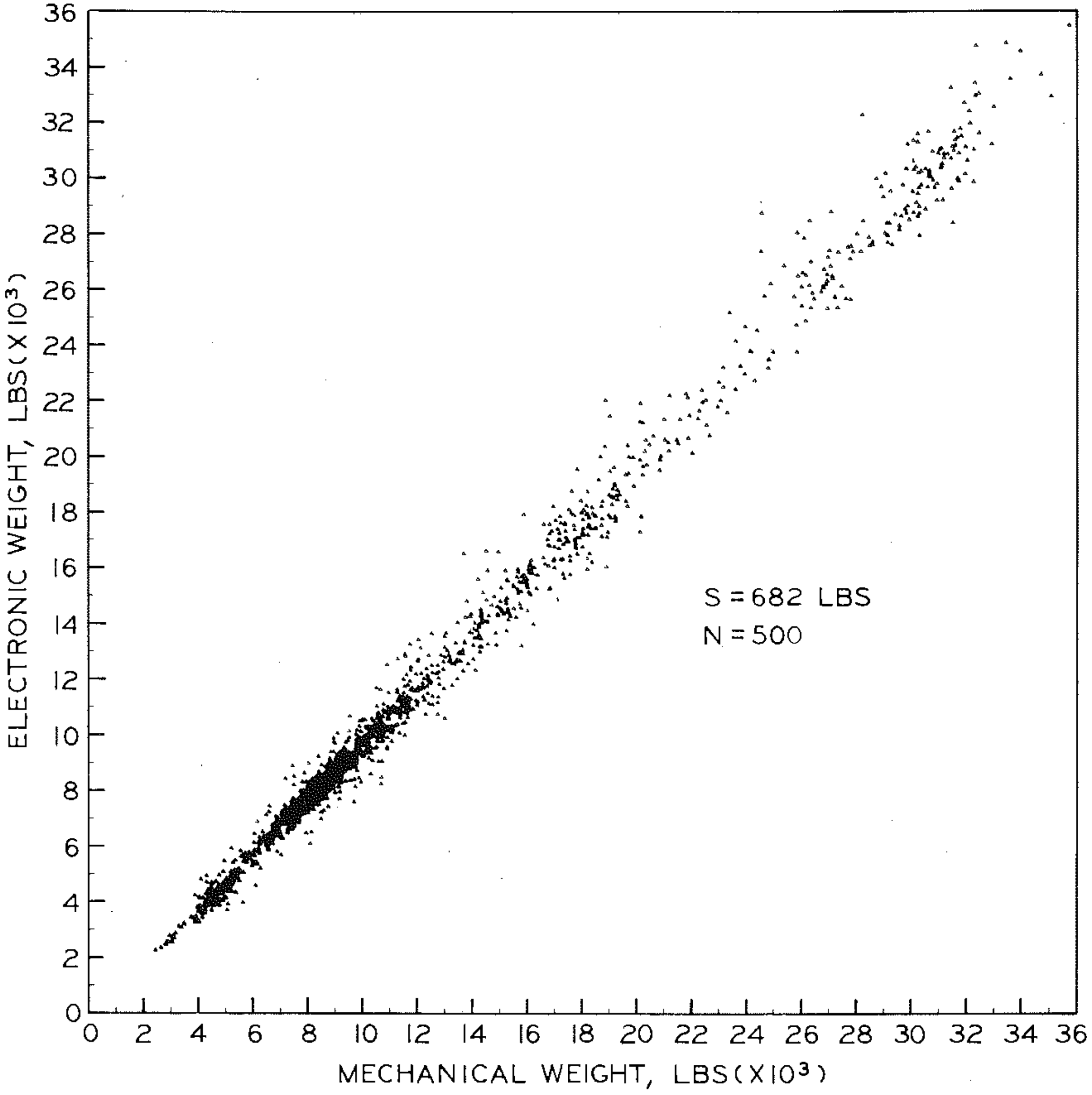


Figure 27. Scatter plot weighing precision using four scales - system operating properly.

The coefficients indicate that the scale outputs are contributing almost equally to the resultant weight. Because of the equal contribution, little emphasis should be placed upon the relative magnitudes of these coefficients. Such outputs are highly intercorrelated, the existence of scale bias and scaling factors will account for slight variations.

To determine system precision as a function of the number of platforms, a stepwise regression of each platform against mechanical weight was performed. This technique determined which of the four scales is the best predictor of mechanical weight and performs a regression analysis using that scale's data. The second best scale is then determined and a regression is performed using data for both scales against mechanical weight. This process continues for all four scales. The result of this analysis is shown in Table 3.

TABLE 3
EFFECT OF WEIGHING PRECISION AS THE NUMBER OF SCALE PLATFORMS ARE INCREASED

Scale No.	Standard Deviation, lb
3	1,252
3 + 4	944
3 + 4 + 2	772
3 + 4 + 2 + 1	682

Results indicate that little benefit would be realized by the addition of more scales. Since the error distributions of each of the platforms are similar, the addition of more platform sampling will provide little additional information for prediction of mechanical weight.

Because scatter plots showed that electronic weight precision tended to decrease with increasing static weight, any attempt to evaluate the effect of speed or vehicle class on dynamic weight accuracy would be difficult. This is because it was not self evident what, if any, relationship existed between typical static axle weight and vehicle speed or class, etc. Therefore, it was considered worthwhile to compare these vehicle groups independently of static weight. To this end, the following analysis was used.

As previously stated, dynamic precision was not uniform over the full static range of axle weights. From a regression analysis point of view, this state of affairs is known as "heteroskedasticity." Moreover, as static axle weight increased, dynamic precision decreased, thus suggesting a monotonic functional relationship between the two. Further, it would be desirable if this relationship could be formed in such a way as to provide a convenient parameter measuring the rate of decrease in precision with static weight. Applied to disparate groups of trucks, this parameter could then be used to assess differences in the scales precision attributable to truck class, type, speed, etc. In order to enable convenient precision comparisons of truck groups the following formulation was used:

$$\sigma_i^2 = kM_i\delta$$

where "M_i" is the "true" or mechanical weight. δ is a parameter which measures the degree of heteroskedasticity. For no homoskedasticity, $\delta = 0$; if measurement error increases in direct proportion to weight magnitude, $\delta = 1.0$.

The general case: What is desired is a maximum likelihood estimate of parameters when,

$$E_i = \alpha + \beta M_i \text{ and } \sigma_i^2 = kM_i\delta$$

Assuming a normal distribution of disturbances, the probability of the i-th value is:

$$P(E = E_i) = (2\pi\sigma_i)^{-1/2} \quad \exp -1/2 \left(\frac{E_i - \alpha - \beta M_i}{\sigma_i}\right)^2$$

For a given sample:

$$P(E_i, E_2, \ldots, E_n) = (2\pi)^{-n/2} \prod_{i=1}^{n} \sigma_i^{-1/2} \quad \exp -1/2 \left(\frac{E_i - \alpha - \beta M_i}{\sigma_i}\right)^2$$

And the likelihood function becomes:

$$L = -n/2 \log 2\pi - 1/2 \sum_{i=1}^{m} (\log k + S \log M_i) - \frac{1}{2k} \sum_{i=1}^{m} \left(\frac{E_i - \alpha - \beta M_i}{M_i \; S/2}\right)^2$$

The customary solution of setting the partial derivatives of "L" to zero is too difficult, so we use another approach:

Step 1. Set $\delta = 0$. This corresponds to the usual solution where $\sigma_i^2 = k$, i.e., ordinarily least squares is applicable. For this case, we calculate α, β, and k and note the value of "L" determined by these parameters.

Step 2. Set $\delta = 0.1$. For this case, the heteroskedastic normal equations result from differentiation of "L":

$$\sum \frac{E_i}{M_i^{0.1}} = \hat{\alpha} \sum \frac{1}{M_i^{0.1}} + \hat{\beta} \sum \frac{M_i}{M_i^{0.1}}$$

$$\sum \frac{E_i M_i}{M_i^{0.1}} = \hat{\alpha} \sum \frac{M_i}{M_i^{0.1}} + \hat{\beta} \sum \frac{M_i^2}{M_i^{0.1}}$$

Again, α, β, and k are estimated and "L" is noted.

Step 3. Same as Step 2 except that δ is stepped in 0.1 increments until it reaches 5.0.

Now the maximum likelihood estimates of α, β, and k will be the one which corresponds to the maximum value of "L". The sampling variance of δ is given by:

$$\hat{\sigma}^2_{\hat{\delta}} = \frac{2}{(\log \in \; M_i^2)}$$

After k was determined for the full truck sample, it was set at this value, and δ's were computed by the above procedure for the variables shown in Table 4. It can be seen from Table 4 that the variations in δ are not visibly related to vehicle speed or class, etc. All $\hat{\delta}$'s are statistically significant, and differences among them are presumed due to random fluctuations in the data[1]. Thus, from these data no evidence can be gathered to justify refinements in the system's program designed to tailor weight computations to vehicle groups, classes, speeds, suspension, axle configuration, etc.

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[1] Since δ was designed as an index of electronic weight precision, and since no systematic or substantial differences in δ appeared with the various vehicles and speed groups, one concludes that the system performs about equally well for all vehicles once the influence of static weight has been removed. If some class of vehicles characteristically has larger than average axle weights, then the electronic estimates will be less precise than what the system usually delivers. This would be, of course, because of the inverse relationship between static weight and system precision. However, δ is a parameter which measures the rate of decrease in precision with increasing static weight, and consequently is not affected by weight distribution ideosyncracies. In addition, all classes showed about the same linear relationship between electronic and static weights.

TABLE 4

TABLE OF δ'S BY SPEED RANGE

Speed	δ
0-10	Insufficient data
10-15	1.37
15-20	1.31
20-25	1.34
25-30	1.38
30-35	1.32
35-40	1.37
40-45	1.38
45-50	1.48
Over 50	Insufficient data

TABLE OF δ'S BY VEHICLE CLASS

Class	δ
2S1	1.33
2S2	1.32
3S2	1.38
2S &2D	1.28
2S3 &3S2	1.38
All but above	1.38

TABLE OF δ'S BY VEHICLE TYPE

Type	δ
Vans	1.37
Flatbeds	1.36
Car carriers	1.33
Liquid carriers	1.38
Bulk carriers	1.36

TABLE OF δ'S BY AXLE CONFIGURATION AND SUSPENSION TYPE

Configuration	Suspension	δ
Single	Leaf	1.31
Single	Air	1.41
Single	Torque	Insufficient data
Tandem	Leaf Equalizer	1.38
Tandem	Air Equalizer	Insufficient data
Tandem	Torque	Insufficient data
Long Tandem	Leaf Equalizer	1.46
Long Tandem	Torque	Insufficient data
Tridem	All	Insufficient data
Single	All	1.32
Tandem	All	1.38
Long Tandem	All	1.46

Scale Spacing

The proper sampling of the rapidly varying vehicle axle loads passing over the scales remains a problem. The weight intelligence from any scale consists of a high amplitude, low frequency (1 to 10 Hz) truckbody load signal, with a low amplitude, higher frequency (20 to 50 Hz) truck axle load signal superimposed over it. The system sampling rate and technique are adequate for the higher frequency axle signals but the more important, high load, low frequency body signals present difficulties.

In an attempt to get an adequate "look" at the body signal, four scales spread at unequal distances apart were used. The overall center-to-center length of 70 ft for the weighing function was thought to be sufficient at the time of system planning and design, and the irregular 10, 20, and 40-ft center-to-center platform spacings were considered economically optimum for an experimental starting point.

There was consideration during project planning of the possibility that regular spacing might prove superior, and the system was designed so that if later tests indicated that significant improvement could be attained by regular spacing, a fifth scale would be installed.

This fifth scale would be placed midway between Scale Nos. 3 and 4. By deactivating the first scale a four-scale, 20-ft regularly spaced system could be tested (the light beam pit is offset between Scale Nos. 3 and 4 to leave a space for the fifth scale, if needed). Later in the project, further consideration of this possible installation was dropped; partly because of its cost, partly because of project delay by other system faults, but primarily because the system precision obtained was very satisfactory and the amount of improvement possible did not warrant the effect.

Section VII of the report, titled "Recommendations," discusses this spacing problem in greater detail and makes recommendations for future experimenters.

An interesting observation is that Scale No. 1 is three times the length of the other three platforms, yet its contribution to weighing precision is the smallest. This is due to the area sampling of weight information. The 9-ft platform was intended for the weighing of tandem and tridem axles in order to eliminate the effects of equalizing suspension systems. The data, however, suggest that this is not necessary and in fact is a detriment to precision. Platforms should be of equal size, equal spacing, and only 2 or 3 ft long.

Dimension System

The accuracy of the dimension system was determined by electronically and manually measuring the width, height, length, and distance between each axle pair while the vehicle was being statically weighed. This operation, which required approximately three months, was performed on 1,000 vehicles. The accuracy of vehicle width and height is necessarily a function of the spacing between sensors. As explained earlier, the spacing is not uniform, the distance between sensors decreases to 1 in. (left and right) for width measurement approaching 8 ft. If the vehicle is near the center of the lane, a 2-in. measurement tolerance can be anticipated. At any other location within the 16-ft lane, an even greater electronic measurement error can be expected. Height increments are 1 ft apart up to 13 ft, and in 2-in. increments to 13 ft - 10 in. (the legal limit on vehicle height in Michigan is 13 ft - 6 in.). Summary results are given in Table 5.

TABLE 5
SUMMARY RESULTS OBTAINED FROM ELECTRONIC
AND MANUAL MEASUREMENT OF 1,000 VEHICLES*

	Number of Samples	One Standard Error, in.	Correlation Coefficient
Length	942	4.6	0.99
Width	914	2.8	0.76
Height	840	5.0	0.97
Axle spacing	3,151	1.5	0.99

*Data generated by system malfunction were removed before analysis.

Vehicle Width

The width error distribution is given in Figure 28. Some difficulties were encountered in measuring static width. It was common for running lights, bumpers, and handles to protrude beyond the vehicle chassis. Bulky loads and liquid carriers were especially difficult. Tie-down ropes, flags, and vehicle "crab" also contributed to manual measurement errors. Modifications were made in the original system design to eliminate the effects of side view mirrors as explained earlier.

Results show a standard error of 16 in. with a positive bias of 2.5 in. The electronic system was within 2 in. of the actual width 57 percent of the

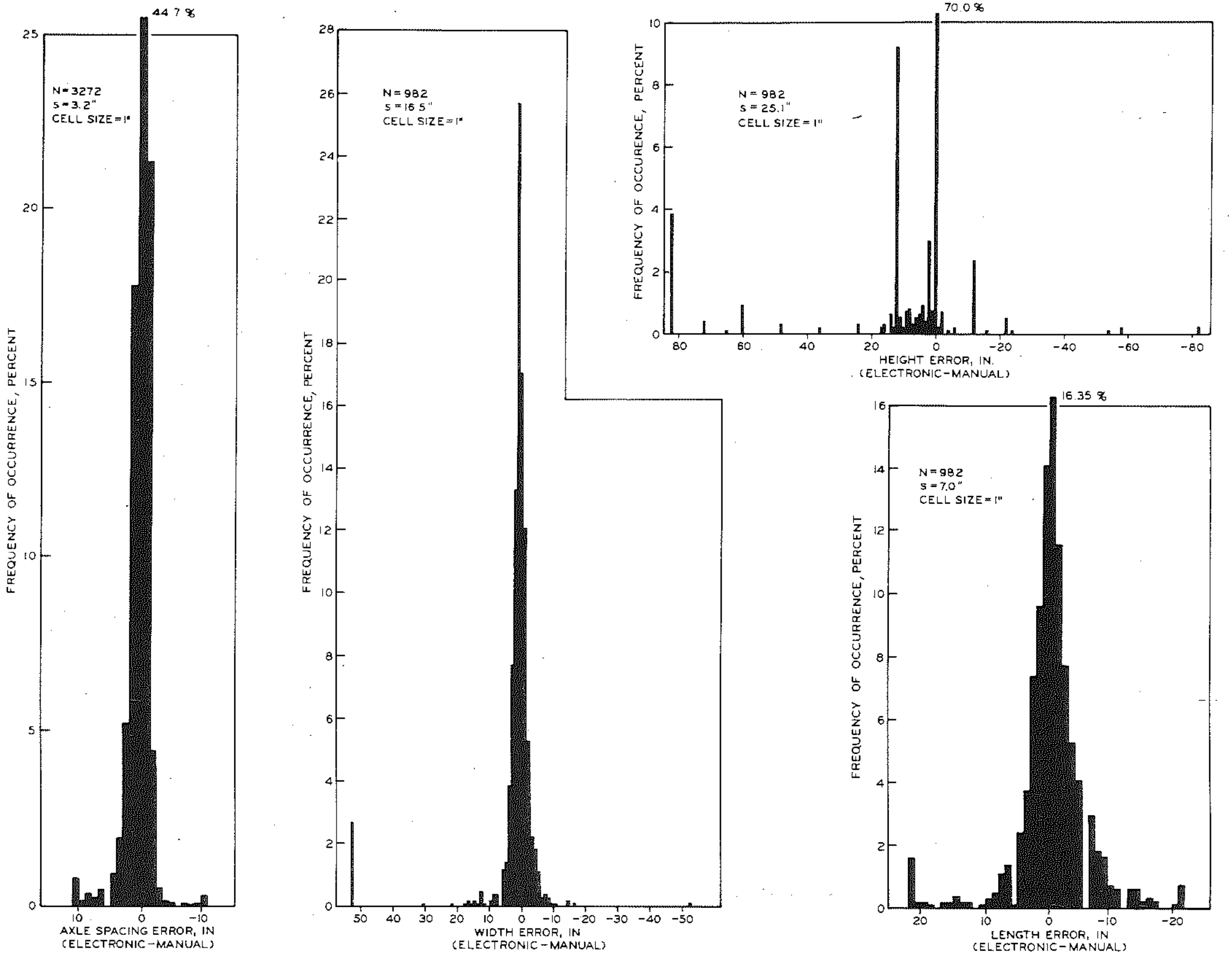

Figure 28. Histograms showing error distribution for electronic measurement of vehicle axle spacing, width, height, and length.

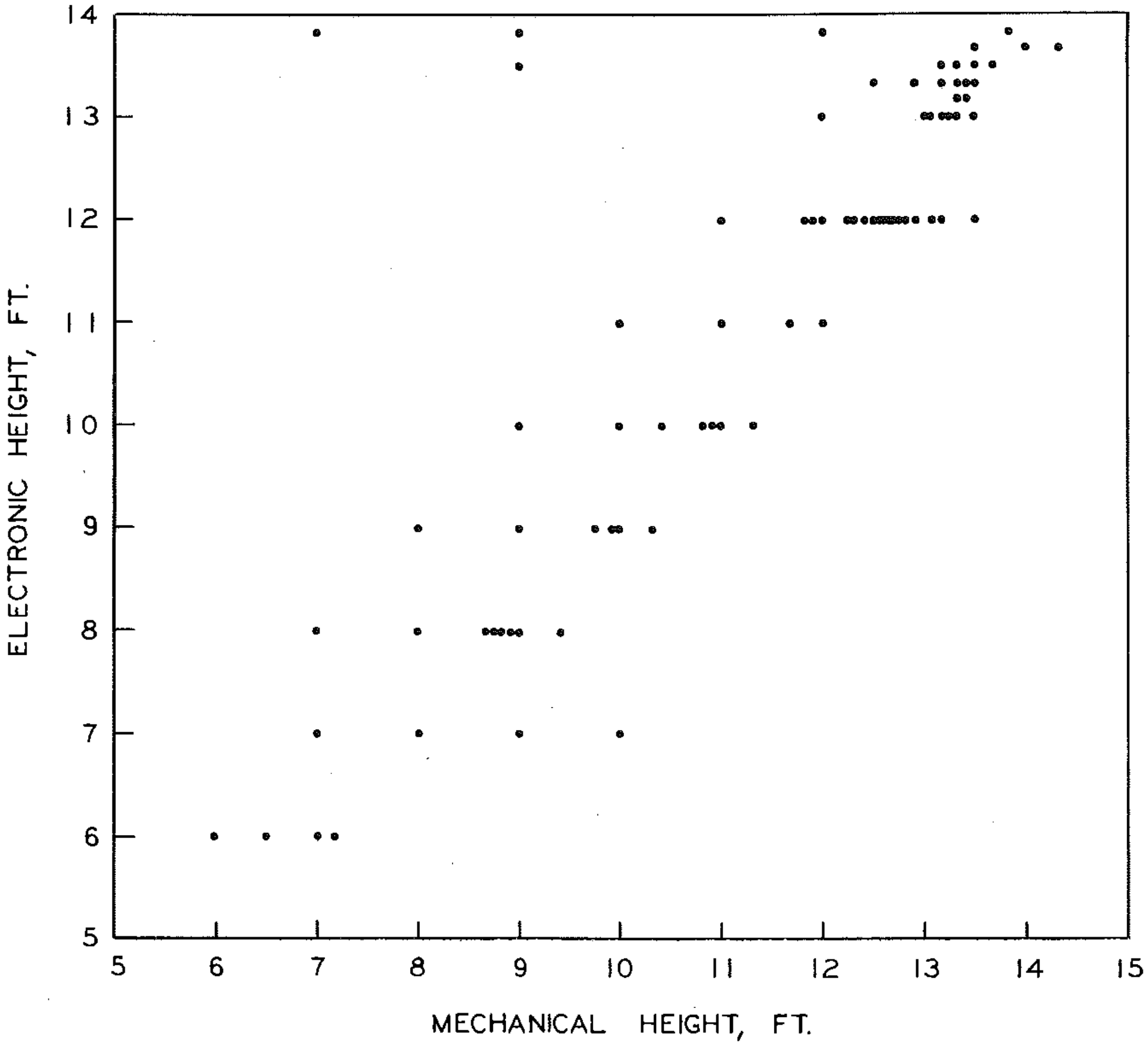

Figure 29. Scatter plot of electronic height measurements vs. manual measurement. Accuracy is limited because of physical spacing and number of height detectors.

time, and within 5 in. 95 percent of the time. The system did not operate properly 2.7 percent of the time. This error is attributed to birds flying through systems and possible errors in manual data transcription. If these explainable errors are removed from the data, the standard error of estimate is reduced to 2.8 in.

Vehicle Height

The height error distribution is given in Figure 28 and a scatter plot in Figure 29. Difficulties were encountered in the manual measurement of this quantity. Flapping tarps, car carriers, and bulk carriers presented the most measurement problems. The positive bias evident in Figure 29 can be attributed to vehicle bounce and sensor spacing. The problem of overhead exhaust stacks was partially eliminated by resetting the height sensors after the tractor passed Scale No. 4. In general, vehicle heights were correct 70 percent of the time. This subsystem failed to operate properly 3.8 percent of the time. This value is similar to the error of the width measurement and appears to be partially due to manual data transcription at the scale site. If data beyond three standard deviations are removed, the standard error of estimate is reduced to 5 in.

Vehicle Length

Vehicle length is measured by the 10 center vertical light beams of the infrared system. Length measurement is calculated from vehicle speed data. Variation in vehicle speed, while traversing the evaluation area, will result in length error. Figure 28 shows the error distribution obtained. The standard error of estimate is 7 in. The electronic length was within 2 in. of the manual measurement 50 percent of the time and within 10 in. of the true length 95 percent of the time. If data beyond three standard errors are removed, the standard error of estimate is reduced to 4.6 in.

Axle Spacing

Axle spacing was required to determine the presence of tandem and tridem axles. Upon identification of the axle configuration, the computer program added the axle weights for each axle grouping for comparison with legal limits established for a given configuration.

The 1,000 vehicle sample resulted in the manual and electronic measurement of 3,272 axle spacings. Results show that the center-to-center axle measurement was within 3 in. of the actual distance 94 percent of the time.

Survey Mode

In the Survey Mode of operation, vehicle classifications can be manually entered on a console as explained earlier. These data are stored on magnetic tape together with the dimensional and weight values for the vehicle for subsequent processing.

In the evaluation of this system component, data for 100 vehicles were entered through the console and manually recorded on paper. Upon completion of the data gathering the results were compared. Of the 500 variables entered, three errors were noted. These appear to have resulted from the faulty operation of one or more of the mechanical stepping switches incorporated into the design of the survey console. Otherwise, the technique employed provides a convenient method of quickly storing vehicle survey data.

VI

SYSTEM COSTS

Giving cost guidance to those planning in-motion vehicle weighing and measuring systems, or presenting meaningful cost figures for the project reported here, is difficult. The project was performed during one of the most severe inflationary periods of U.S. history, and also during a period of tremendous advances in electronic instrumentation and computer science.

Where inflation has exerted pressure towards increased labor, material, and equipment costs, advances in the electronics industry have tended to effect significant decreases in system component costs. These factors coupled with the fact that this system is a first prototype and, as such, is inherently expensive; plus the fact that the knowledge gained in this experiment obviates the need for many of the expenditures made here, gives the whole cost matter a somewhat questionable status.

A duplication, not necessary in future systems, was the complete breadboard system, assembled prior to final system installation. Also, many changes and modifications were required throughout the project as dictated by the findings of interim experiments and the time consuming and expensive troubles encountered here should be avoidable for future experimenters.

Because of the integrated nature of the four subsystems making up this overall system, it is difficult to give separate subsystem costs for those considering an installation incorporating anything less than all of the four subsystems. However, an attempt has been made to do this, but the resulting totals should be considered as highly speculative.

Total System Costs

The total funds expended on this project equaled approximately $675,000, as follows:

Feasibility Study	$ 30,000
Part A	220,000
Post Part A	56,000
Part B	226,000
Part C	63,000
Miscellaneous	80,000
	$675,000

The miscellaneous category covers funds expended by the Laboratory for administration, engineering, analytical work, and many required minor contractual items.

In the total cost tabulation which follows many amounts are estimates in that they were originally included in the overall bid or cost of a number of equipment and performance items. They have been broken out by estimating their contribution to a total phase cost. In addition, it is important that the reader note that the final total component item estimates do not equal the $675,000 total estimate for the project.

This should be understandable if the reader recalls that this project entailed two complete duplicate experiments; a breadboard system and a final fully operational system with many of the items of the breadboard system being completely rebuilt or replaced in the final experiment. For example, the $71,000 cost tabulated for the dimension system is almost totally that for the final system as it was necessary to completely replace the original dimension hardware and to construct a pit as part of the final system. Consequently, the cost of the breadboard dimension system is not included in the tabulation.

Also, the Laboratory's costs over the eight-year duration of the project for maintenance, replacement, refurbishing, lightning damage repair, modifications, etc., are not included.

Present System Costs

Electronic Scales

1) Four pits	$36,000
2) Four platforms plus all mounting hardware	28,000
3) Associated electronics including load cells, power supplies, amplifiers, A/D converter, multiplexer, tape switches, wiring, etc.	27,000
	$91,000

Dimension System

1) Physical installation including pit, platform, overhead truss, dehumidifier, wiring, installation, etc.	$28,000
2) Sensors, sources, mounting and enclosing hardware and installation	43,700[1]
	$71,700

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[1] Philco-Ford estimate

Speed and Classification System

1) Bridge-mounted transceivers, amplifiers, cable drivers, and recording and display console	$13,600
2) Cable and installation (1-1/2 miles)	4,400
	$18,000

Traffic Survey System

1) Survey console	$21,000

Closed-Circuit Television

1) Cameras and monitor	$13,100
2) Cable and installation (1,300 ft)	1,000
	$14,100

Major Instrumentation

1) Digital computer, modified and with software	$ 66,300[1]
2) Digital magnetic tape recorder	40,200[1]
3) Teletypewriter	10,400[1]
4) Weighmaster console	12,800[1]
5) Communication and test network	13,000[1]
6) Preprocessor, including tape switch encoders, driver amplifiers, valid weight detectors, power supplies, voltage status boards, generator board, length indicator and enclosure	20,600[2]
	$163,300

Site Installations

1) Scalehouse bypass lane	$ 5,000
2) Electronic scale area bypass lane	8,400
3) Bituminous shoulder paving	2,200
4) Site power and lighting	9,000
5) Shoulder enclosure (housing electronics adjacent to scales)	2,000
6) Site signing	3,100
7) Cables from scales to scalehouse and in scale area	4,700
	$34,400

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[1] Philco-Ford estimate.

[2] Philco-Ford estimate plus $500 for enclosure.

Debugging, Calibration and Testing	$83,300[3]

Summary and Total

Electronic scales	$ 91,000
Dimension system	71,700
Speed and classification system	18,000
Traffic survey system	21,000
Closed-circuit television system	14,100
Major instrumentation	163,300
Site installations	34,400
Debugging, calibration and testing	83,300
Total -	$496,800

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[3] Philco-Ford estimate plus $25,000 for Laboratory costs.

If all of the costs of engineering, administration, the feasibility study, duplications as in Post Part A and with respect to the dimension system are added to the above $496,800, the figure would exceed the $675,000 total project cost. This results from the Philco-Ford Corporation's claim (and included in their estimate) that their costs were some $70,000 in excess of the amount of their contract. Also, many items in the contract would not require repeating in another system such as, training programmers, basic programming, etc.

Future System Costs

The future system costs which follow are based on a combination of Research Laboratory and Philco-Ford Corp. estimates of the cost reductions which can be effected in future systems. They envision a simpler, low-profile electronic scale embedded in the pavement surface rather than the complex and expensive pit-platform installations of this study.

Item	Costs	
	One System	Ten Systems
Electronic scales	$ 40,000	$ 360,000
Dimension system	40,000	360,000
Speed and classification system	16,000	145,000
Traffic survey system	15,000	120,000
Closed-circuit television	6,000	54,000
Major instrumentation	100,000	850,000
Site installations	26,000	230,000
Debugging, calibration and testing	20,000	100,000
Totals -	$263,000	$2,219,000

Such estimates must be considered as guides at best. The U.S. economic situation of recent years is so highly variable and this, in conjunction with the variability of users needs; the increases in labor and material costs; the significant decreases in sold-state instrumentation and computer costs, coupled at the same time with significant cost increases for other types of instrumentation testifies to the difficulty of arriving at any meaningful future system cost estimates.

VII

CONCLUSIONS AND RECOMMENDATIONS

Throughout this project many improvements were made in system design, mechanical and electrical components, and structural integrity. However, many were not made because of other considerations. Solutions to most of the problems were apparent. Rectification of these deficiencies did, in general, necessitate the expenditure of large sums of money and time. Also, during the evaluation of the system, new products became available; thus, existing components, integrated circuit technology, and computer developments became obsolete. Future systems should incorporate the latest techniques in components and instrumentation.

Scale Platforms

Because of their below ground location, scale pits invariably exhibit a highly humid, corrosive atmosphere. Therefore, the use of such pits should be minimized. Wheel load transducers are now commercially available. These units being only 3 to 4 in. in depth are easily installed. Weighing less than 1,000 lb, their resonant frequency is above 200 Hz and out of range of vehicle frequencies. The transducers, two for each axle weight, are linear within one percent and usually have temperature compensation.

If pits are required, such as for determination of vehicle width, they should be carefully constructed. The use of drains, epoxy coated walls, and a vapor barrier ceiling are highly recommended. A dehumidifier should be considered for removal of corrosive salts and other chemicals that are held in atmospheric suspension. All wiring in the pits should be shielded and encased in RHW or PVC jackets. Signal cables should be placed in conduit with provisions for drainage. And, finally, no electronic equipment should be placed inside the pit.

Concrete - Bituminous Pavement

Smooth approach and passage through the scale area is highly desirable. Such pavement surfaces permit the vehicle to run flat with a minimum of axle and body oscillation; thus, resulting in increased weighing precision. Since most vehicles are critically damped, the length of this smooth approach should be at least 120 ft for vehicles traveling 50 mph. If the desired smoothness is not attainable, reduction of vehicle speed will be required to achieve the same precision.

Dimensioning System

The measurement of vehicle size in this study had two purposes. Determination of width, length, and height for enforcement; and vehicle survey information. These data are valuable for determination of capacity requirements for future highways.

If only enforcement is required, a much simpler system using fewer numbers of light arrays can be used.

Although the infrared subsystem has performed satisfactorily, improvement is still possible. Pulsed lasers with beam splitters and corner cube reflector prisms offer interesting possibilities and should be investigated.

Scale Switches

The most serious problem, resulting from system design, was the operation of the tire-actuated switches. Their proper operation was fundamental to the entire system. Elimination of the switches would have required a complete redesign of system logic and computer program. Therefore, this alternative was not feasible.

In the design of future systems, all mechanical devices, such as the scale platform surface switches, exposed to the environment or the vehicles themselves should be eliminated. Their functional requirements should be replaced by solid state devices. For example, the tire-actuated switches can be replaced by computer programming. The program would incorporate a scale active process; a subroutine which would store 10 to 15 weight samples. These samples would be input to an exponential delay process and the derivative computed. When the derivative was found to be zero, the axle would be fully on the platform. Then, depending upon the scale buffer size, the mean weight sample could be computed. The order of the exponential delay would depend upon platform response time and pavement roughness, and the optimum order would be determined by examination of the analog waveform produced by each platform under dynamic conditions.

Computer

Mini-computers can be easily adapted for use in vehicle weighing systems. They are smaller, faster, and less expensive than the 1960 vintage models. They can be easily interfaced with analog-to-digital converters, multiplexers, and system logic. Computers for dynamic weighing should have the following minimum requirements:

1) Machine cycle time of 2 micro-seconds or less
2) minimum of 12-bit word length
3) minimum of 8,000 words of read/write core memory

4) minimum of two levels of true priority interrupt
5) I/O channel interface or data break (high speed)
6) separate 6-bit I/O channel (slow speed)
7) protection from power line voltage surges and over-voltage protection on data lines.

Peripheral equipment such as a high-speed teletype, digital magnetic tape unit, and paper tape input-output device are also recommended.

Vehicle Simulation

The electronic system required for weighing and dimensioning of vehicles in motion is generally complex. In order to be assured of its proper operation, a vehicle simulator should be included in the system design. This device would be used to simulate a vehicle with known characteristics traversing the system. Simulation outputs should be electrically inserted in place of normal transducer signals, thereby testing all system components except the transducers themselves. This capability will be extremely useful for system check-out, diagnostic testing, and operator training.

Computer Interface

Design of future systems should provide some form of isolation of the computer from cables transmitting data to and from transducers and vehicle control signs, as voltage surges from induced line currents can destroy computer components.

Since data entering and leaving the computer are in digital format, light isolating modules producing a 1 or zero output can be effectively used. This technique would completely isolate the computer I/O components from damage due to indirect lightning strikes. If it is desired to isolate the interconnecting cable, this technique might be used at both cable ends.

Lightning Protection

In planning a future installation, careful consideration should be given to lightning protection due to the low voltages used in the electronic circuitry. Electric power for lighting and other auxiliary uses should be isolated as much as possible from both electronic circuitry and data transmission lines. If buried cable is used, select high-dielectric cables such as double-sheathed, Alpeth or Stalpeth cables for high-lightning areas. Placement of spaced shield-wires above the cable lowers the instance of lightning damage in critical areas. Using a grounded metal conduit might also be considered. Arrestors and zener diodes in critical locations should be used; although a completely lightning damageproof installation cannot be obtained at a reasonable cost, judicious measures should reduce cost of replacement and down time.

Another measure to reduce the possibility of lightning damage is to place the evaluation system close to the scalehouse, thereby reducing the length of cable required, and precluding the generation of induced voltage. Appropriate signing located beyond the evaluation lane would direct the driver to return over alternate scales for static measurements if violations are detected.

Electronic Equipment

Experience with power supplies, signal conditioning units, and readout, printout, or control equipment has indicated the necessity for maximum reliability. Many highway scale installations operate on a 24-hr day basis. This type of duty dictates the use of solid-state instrumentation and a minimum of devices incorporating mechanical movements (relays, stepping switches, etc.). Such equipment often involves higher initial cost, but lower operating cost and greatly reduced maintenance requirements with greater reliability are attained.

Design of Weighing System

Designers of future weighing systems may find the following methodology useful.

This exposition is concerned with the problem of the "best" sampling plan for the electronic weighing of vehicles in motion. Briefly, the physical layout consists of one or more axle platforms spaced sequentially in the weigh station roadway. Each platform produces an electrical voltage proportional to the axle weight.

The problem of dynamic weighing is complicated by the unavoidable fact that trucks vary in both their primary frequency, body resonance, and the frequency produced by their pass-by speeds. The problem can be viewed from the standpoint of systematic sampling if it is assumed that the scales are placed equal distances apart.

Weigh stations are required to weigh all commercial vehicles, encompassing a wide range of truck types, loads, and speeds. Thus, the scale system will experience a broad distribution of primary frequencies. The distance between the first and last scale can be thought of as a "sampling window." Loaded and unloaded vehicles will present a varying amount of primary frequencies to this window.

Having knowledge of the highest frequency present and a design speed for the system, the optimum number of scales, scale spacing, and length of platforms can be determined.

1) Use the dynamic force measuring techniques of the Michigan Department of State Highways and Transportation (13) or the General Motors Corporation (14) to record the force data from a widely divergent set of loaded trucks passing over the proposed site (or a similarly constructed site) at design speed.

2) Compute the power spectral density and autocovariances for each test and pick the worst case condition. That is, the highest frequency for which dynamic loads are a significant portion of the static load.

3) Use the autocovariance from Step 2 in the formula:

$$B = \frac{T\,\sigma_x^2}{2(T - \tau)\int_{-T}^{T} C_x(\tau)\,d\tau}$$

where:

B = effective data band width
T = length of test run in seconds
σ_x = variance of the force signal
τ = the lag value used in computing the autocovariance
$C_x(\tau)$ = autocovariance estimates

4) Use B from Step 3 in the formula:

$$L = \frac{Spd}{2BE^2}\left(\frac{\sigma_x}{\mu_x}\right)$$

where:

L = length of the scale measuring area
Spd = scale system design speed
σ_x = standard error of the force data
μ_x = average force for the test run
E^x = normalized standard error desired for the weight estimates.

5) Determine the distance covered at design speed by one cyclc of the highest effective frequency and place two platforms in this distance. Repeat the process until the distance L from Step 4 is covered.

To reduce quantization error (12) the platforms should be just large enough to accomodate the largest expected tire footprint. Only the peak load value should be retained during passage of an axle.

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8. Trott, J. J., and Whiffin, A. C., "Measurements of the Axle-Loads of Moving Vehicles on Trunk Roads," Roads and Road Construction, V. 43, N. 511, July 1965.

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12. Bendat, J. S., and Piersol, A. G., Measurement and Analysis of Random Data. John Wiley & Sons, New York, p. 281.

13. Darlington, J. R., "Dynamic Load Aspects of Truck Size and Weight," Michigan Department of State Highways and Transportation, Research Report R-858, August 1973.

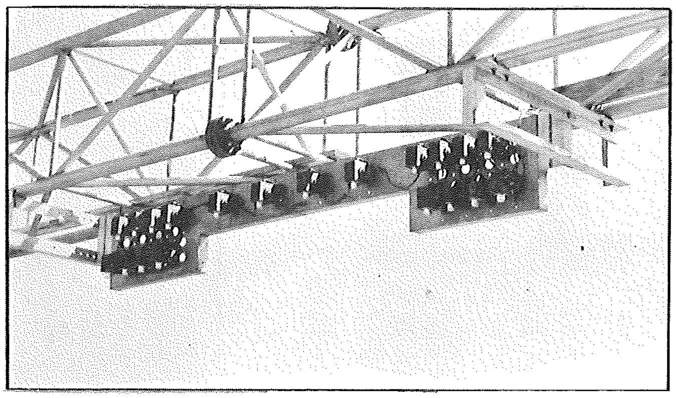
14. Whittemore, A. P., et al, "Dynamic Pavement Loads of Heavy Highway Vehicles," NCHRP Report 105, Highway Research Board, 1970.

APPENDIX

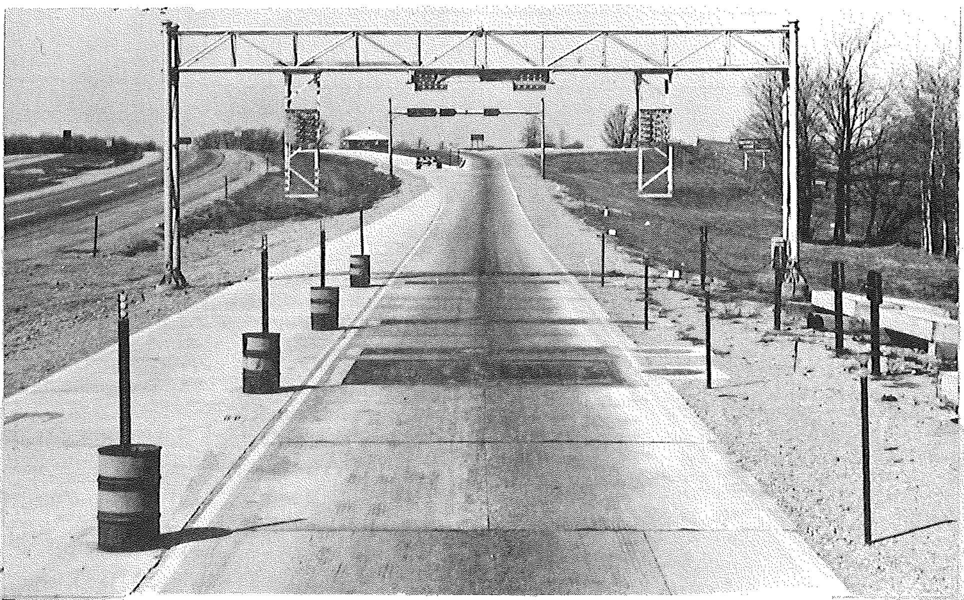
Because an excessive number of photographs in a report can be distracting to the reader/student, and because of the large number of photos necessary to show the many subsystems and components of this study, it was decided to bring all of these pictures together in this pictorial section. Photos have been placed elsewhere in the report where it was felt they would contribute to understanding and clarity of the text.

ORIGINAL "BREADBOARD" SYSTEM BY EPSCO INC.

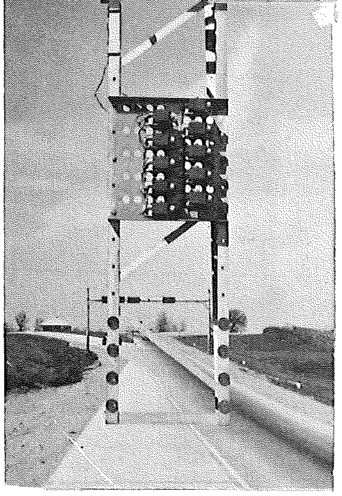
(Part A -- July 1961-March 1964)



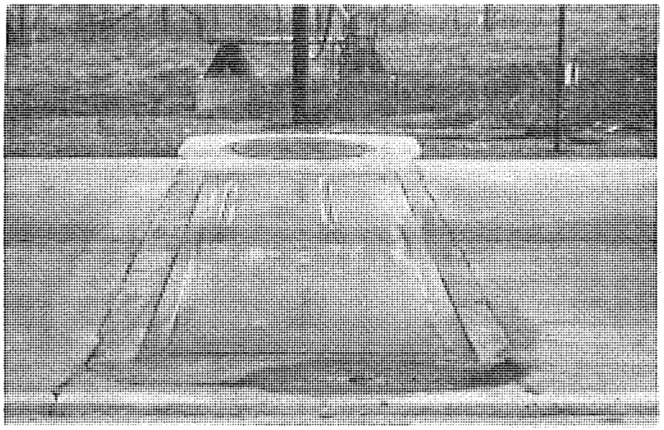
View B



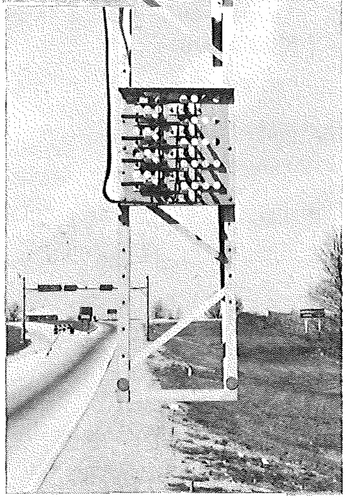
View A



View E

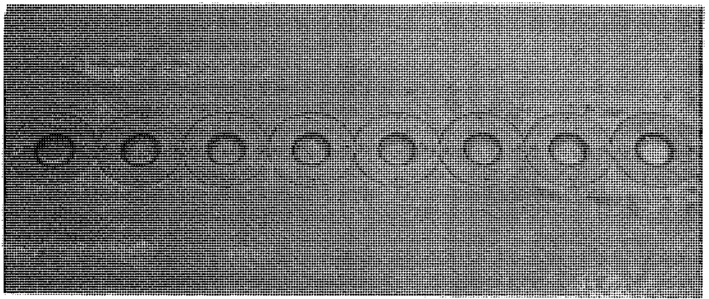


View C

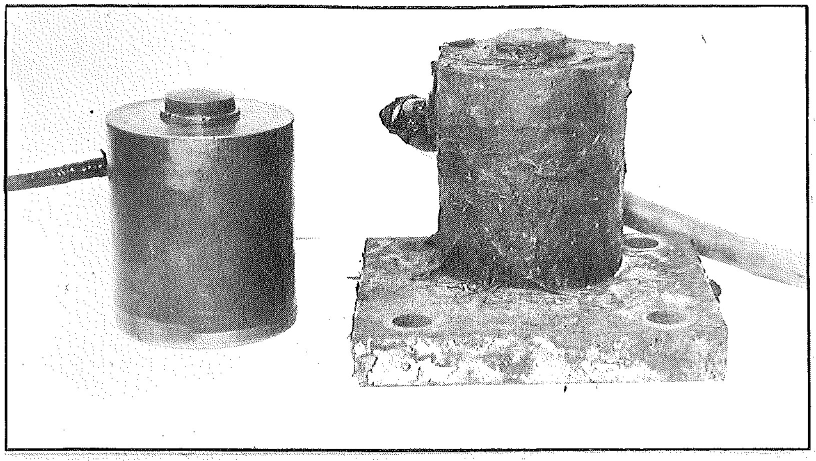


View F

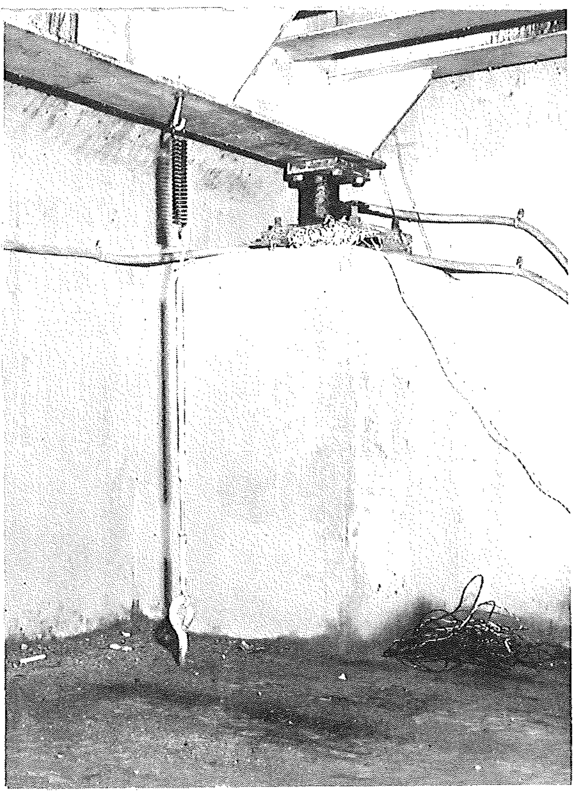
View D



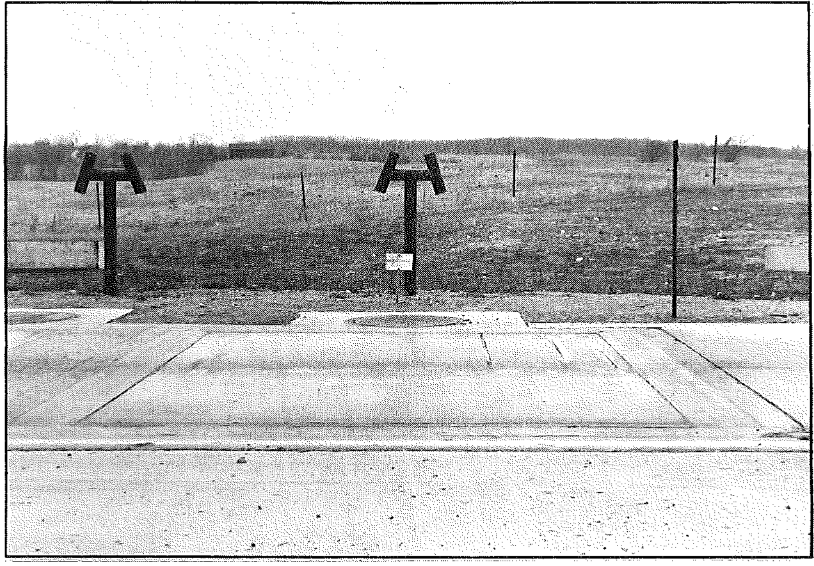
View A gives a vehicle operator's view of the original dimension system. View B shows the width and length measurement light sources and View C shows the detector light ports set into the surface of the fourth electronic scale (View D is a close-up of a row of the ports). Views E and F show respectively, the height, light sources and detectors.



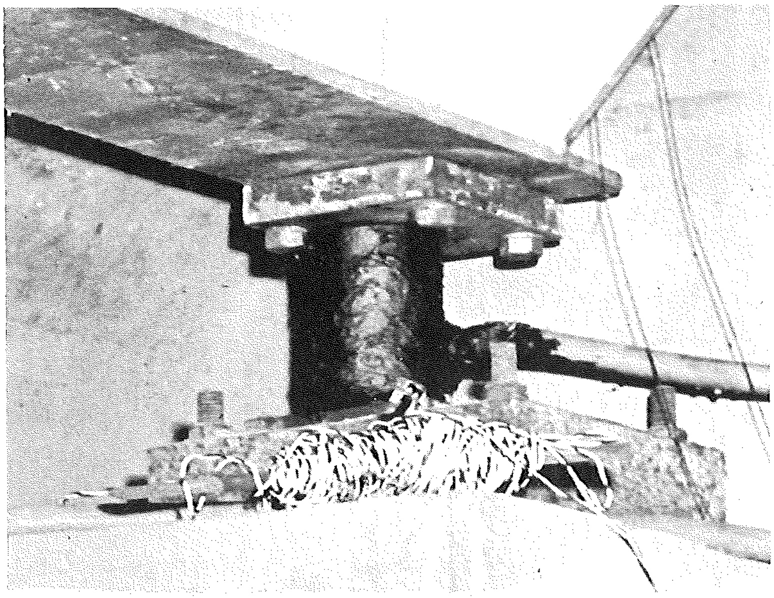
View of load cell before and after waterproofing - covered cell secured to mounting plate.



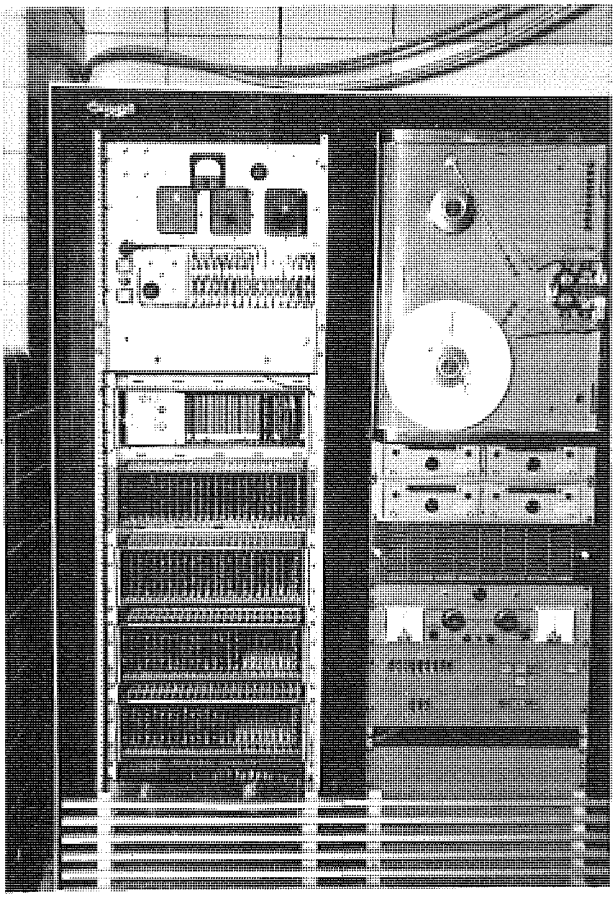
View of scale pit corner showing pre-load spring.



Large scale sealed in place - pit vent stacks visible behind scale.

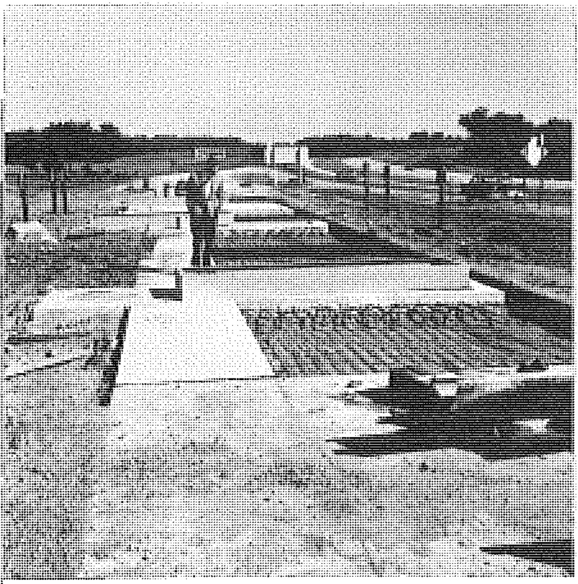


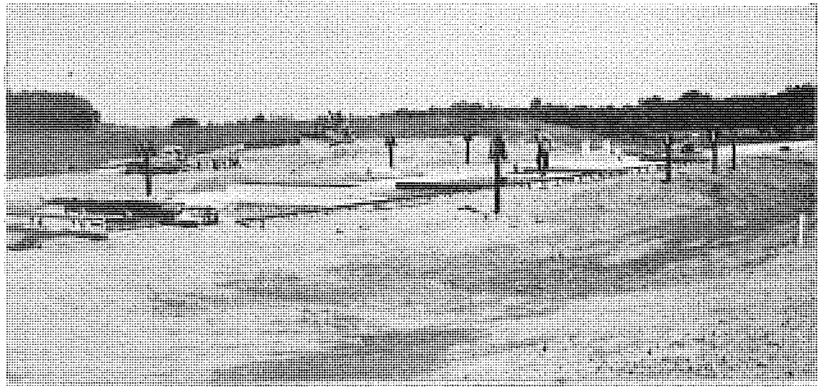
Load cell in position under corner of large scale platform.

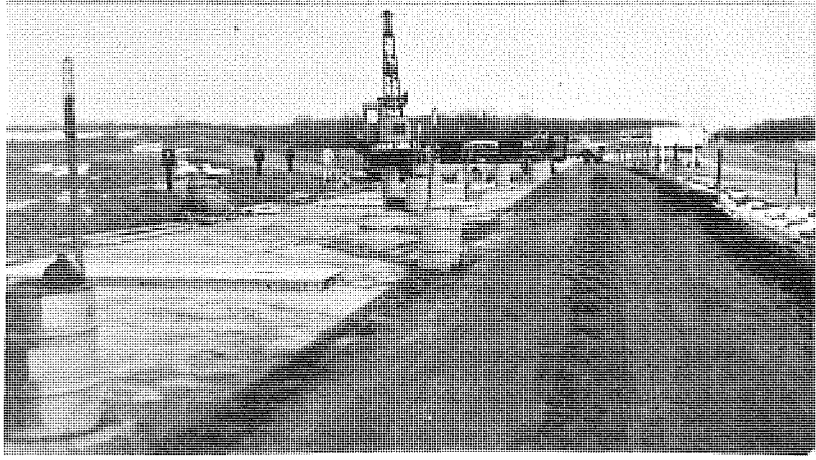


Rack mounted electronics of "breadboard" system. Cabinet contains tape recorder, multiplexer, analog-to-digital converter, scale amplifiers, logic circuits, registers and so on, for both weighing and dimensioning functions.

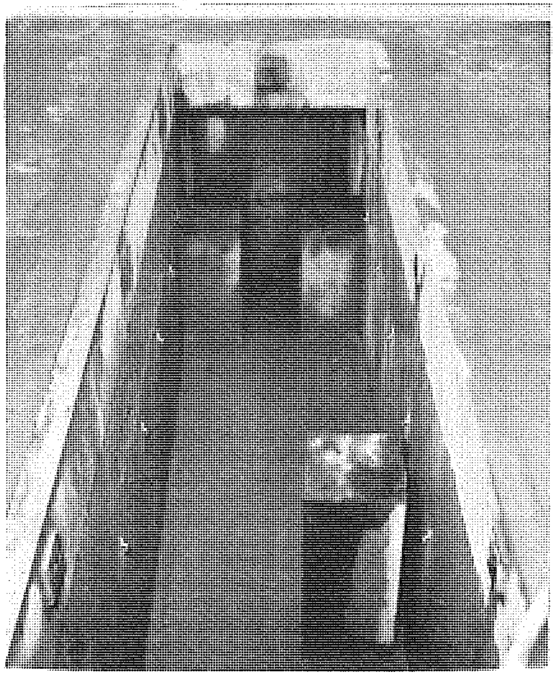
Three views of initial system construction.

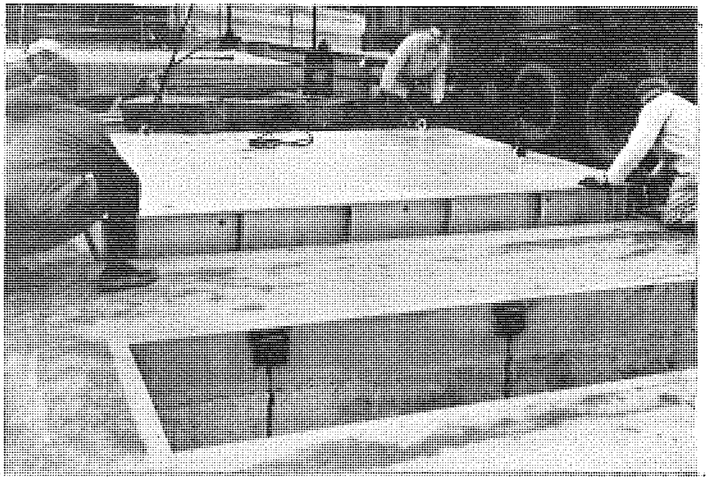




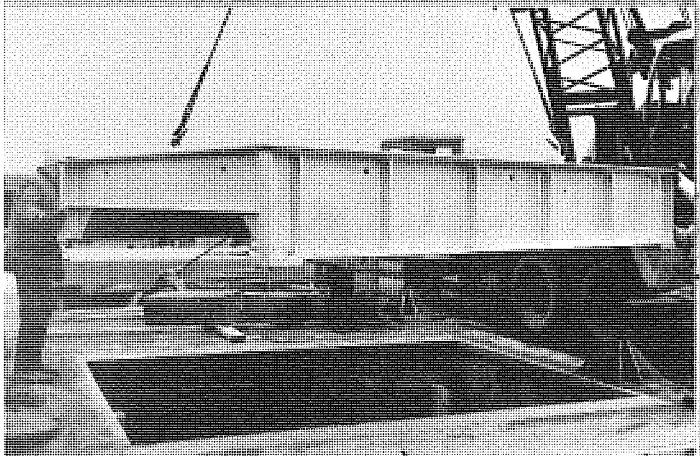


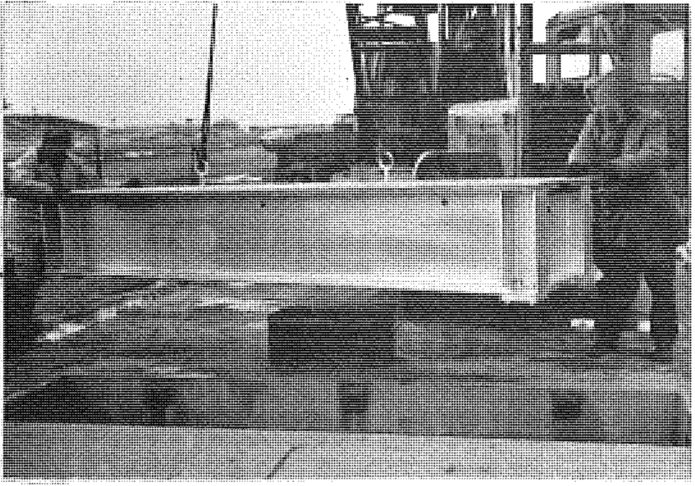
One of small scale pits as originally constructed.

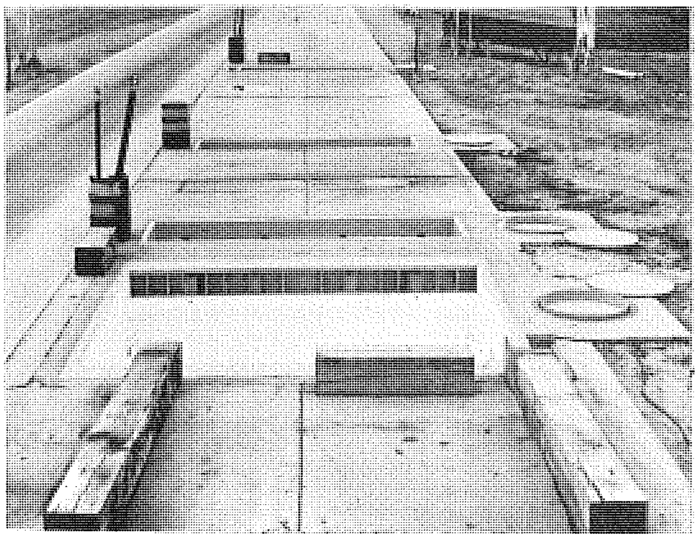




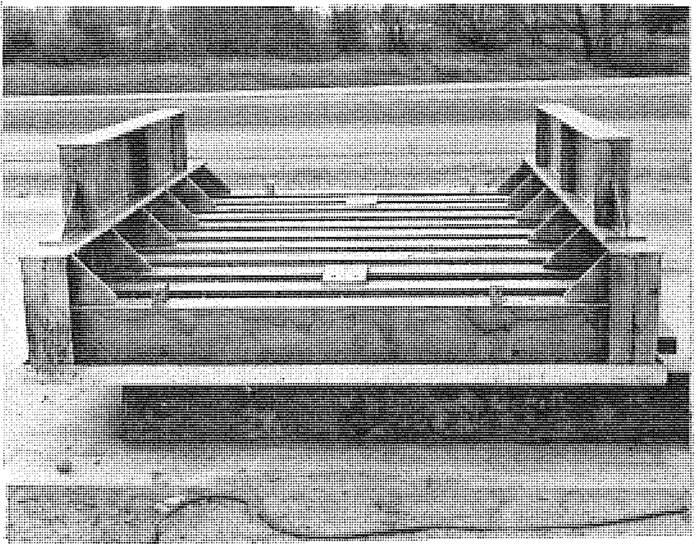
Two views of actual installation of large platform (left) and one of the small platforms (below).



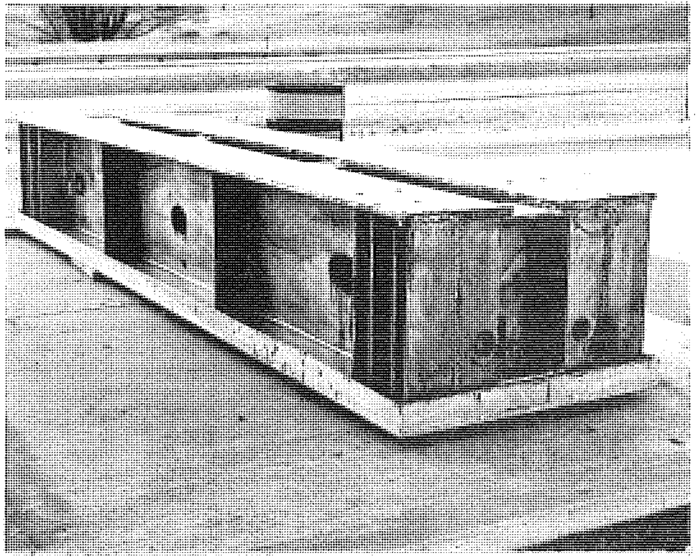




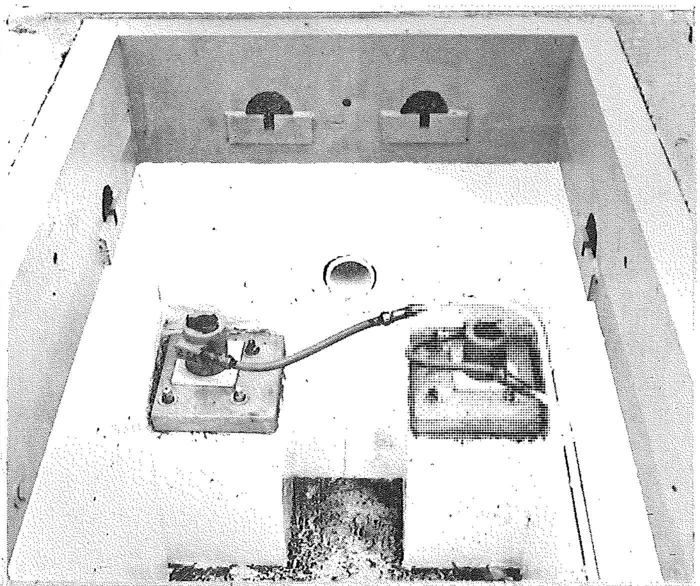
View of site with all pits ready to receive platforms.



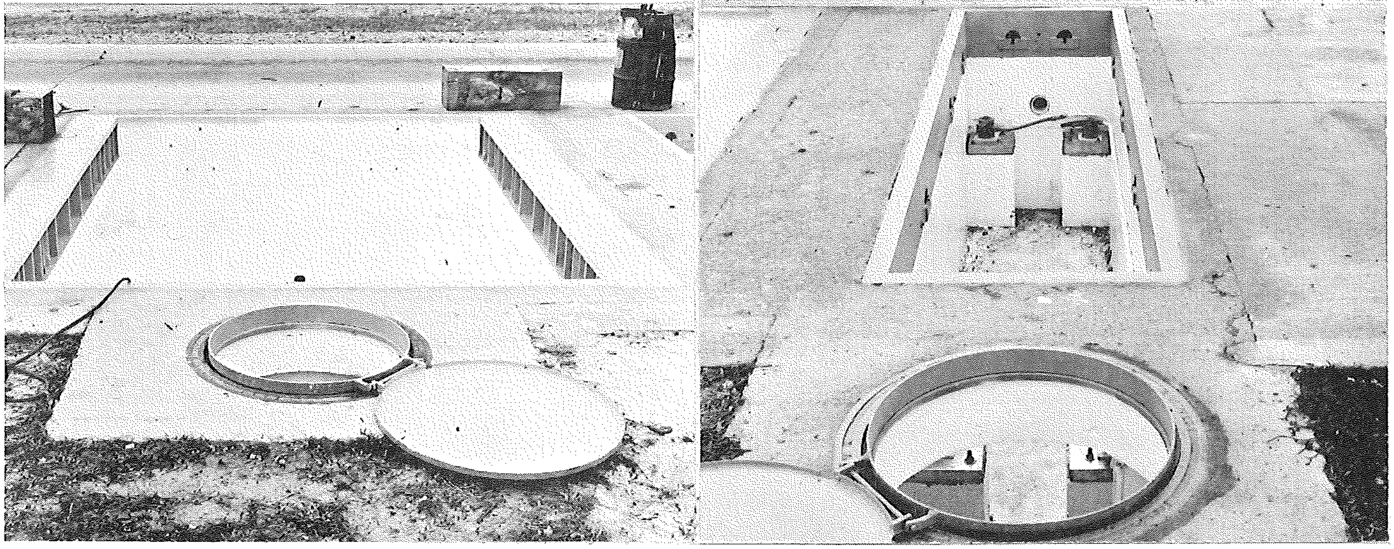
Large scale platform (upside down) ready for installation-galvanized and covered with rust preventative.



Small scale platform (upside down) ready for installation.



View of non-access end of small pit showing load cells on pillars; and in upper pit frame, anchors for both transverse and longitudinal check rods.

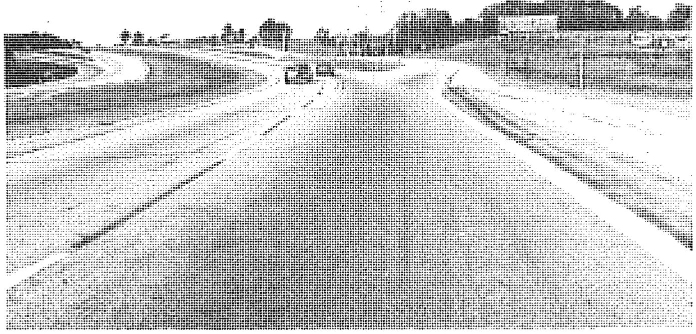


View of large scale pit (left) and one of small scale pits (right), ready for platform installation (white epoxy paint tends to camouflage cells and pillars in large pit).

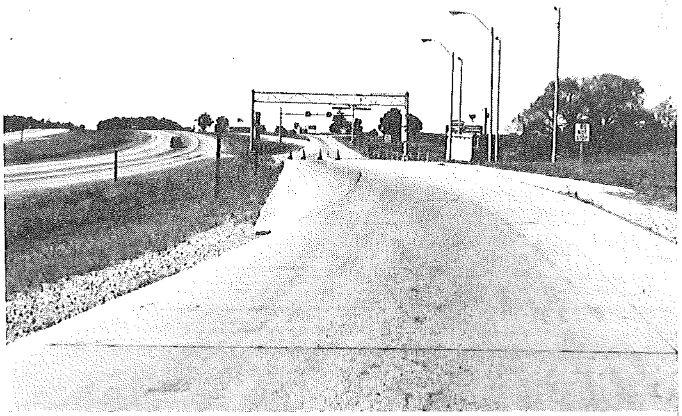
FINAL DYNAMIC WEIGHING AND DIMENSIONING SYSTEM
BY PHILCO-FORD CORP.

(Part B - December 1964-February 1966)

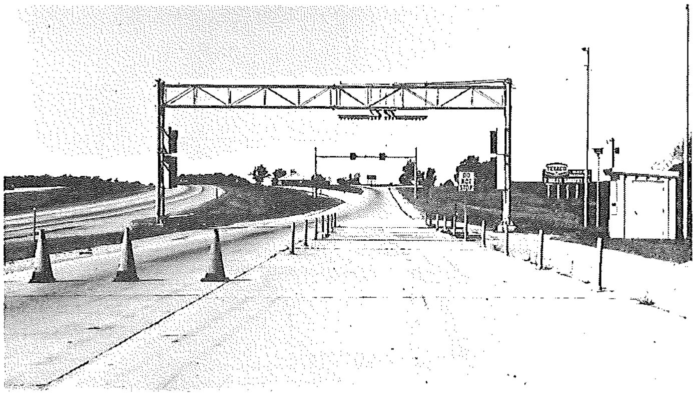
The reader is first taken, pictorially, for a trip through the entire installation—seeing selected system views as a using truck driver would see them. Next there are a series of pictorials of the various subsystems and their component parts.



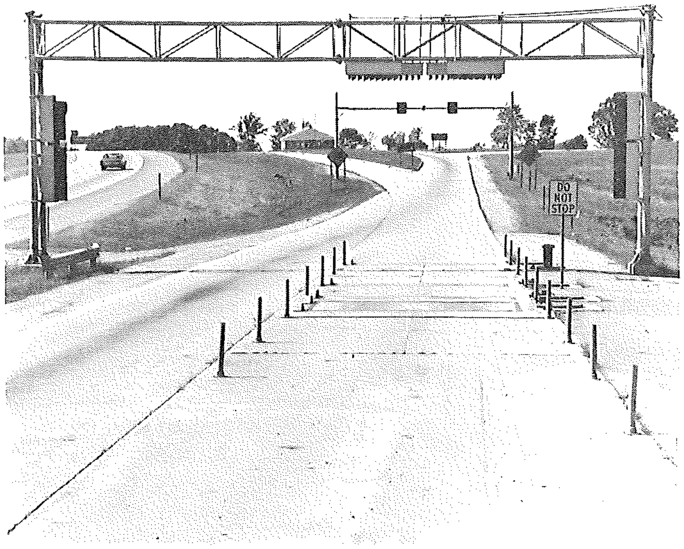
On westbound I 94 approaching off-ramp.



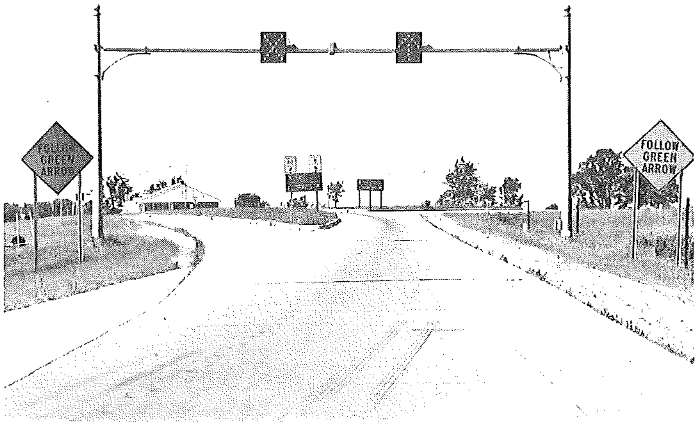
Evaluation area coming into view.



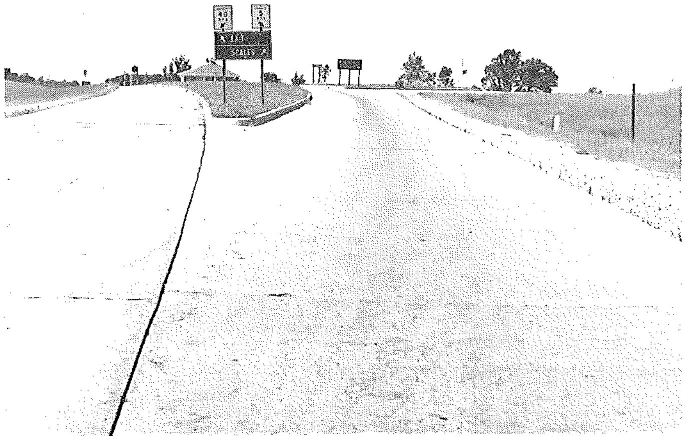
150 ft from system entry.



40 ft from system entry.

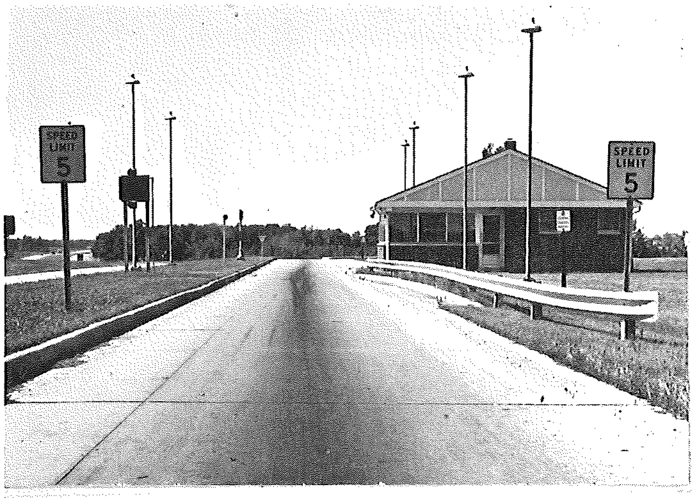


Having been weighed and measured and found to be in violation overhead signs block bypass lane and direct vehicle to scalehouse lane.



Approaching gore between bypass (left) and scalehouse (right) lanes.

Approaching scalehouse.

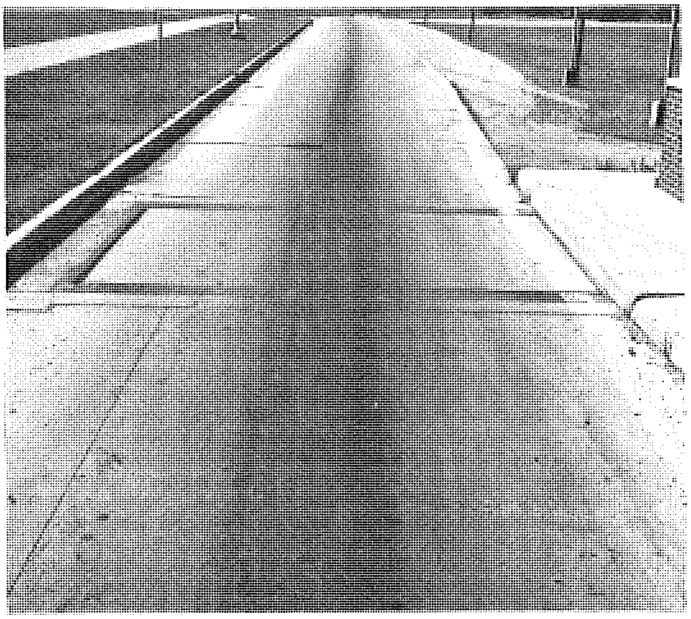


About to roll onto mechanical scale in accordance with weighmaster's directions - public address system and Stop-Go signal.

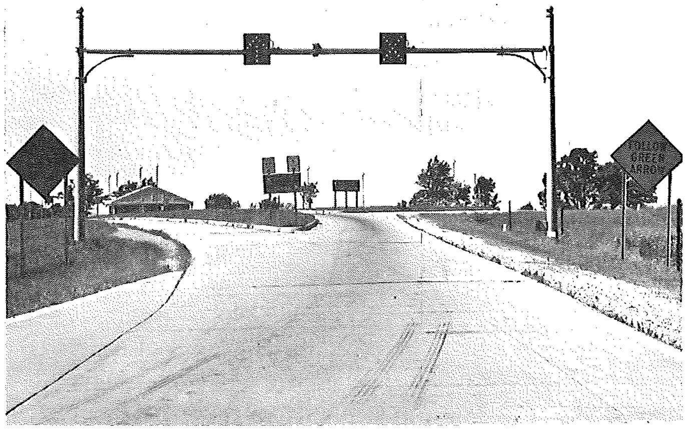
Should a vehicle found to be illegal take the bypass lane in violation of the overhead sign directions it would be presented with this flashing message to take the turn-off, circle around behind the scalehouse and then enter the scalehouse lane and stop on the mechanical scale (no message is visible when the sign is not illuminated).

Returning to I 94 via the bypass lane.

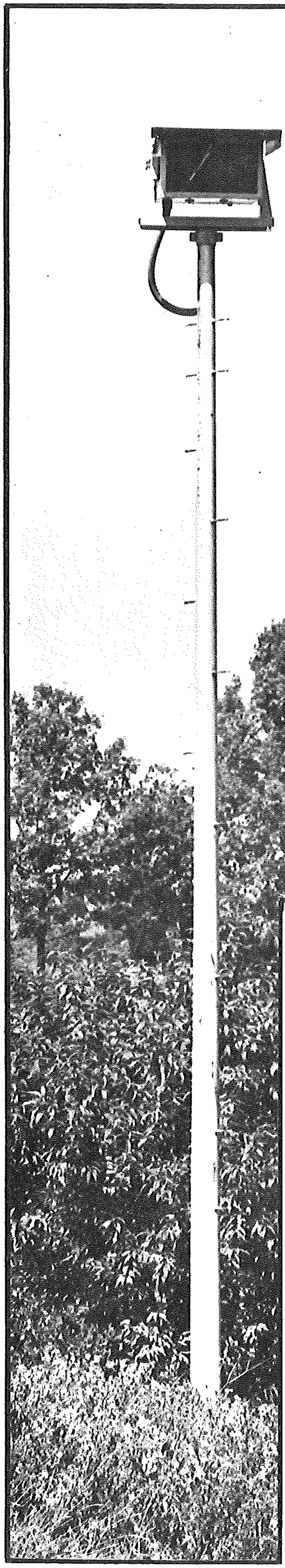
Speed reduction area for entry onto mechanical scale.

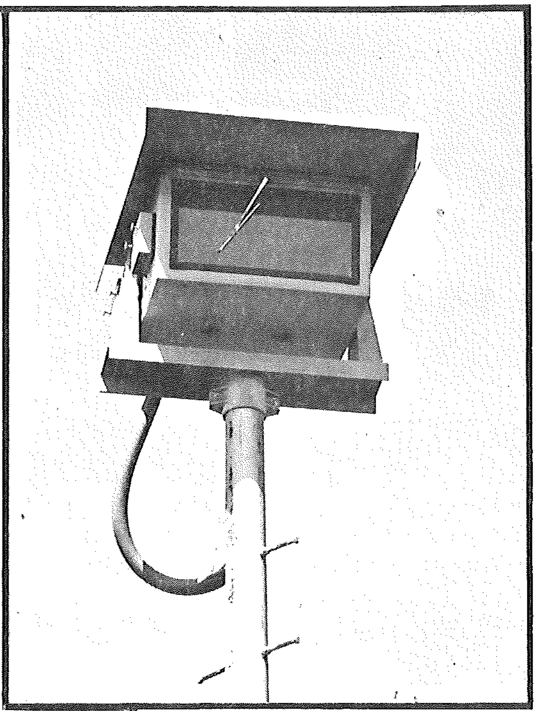


Returning to I 94 after being cleared by weighmaster.



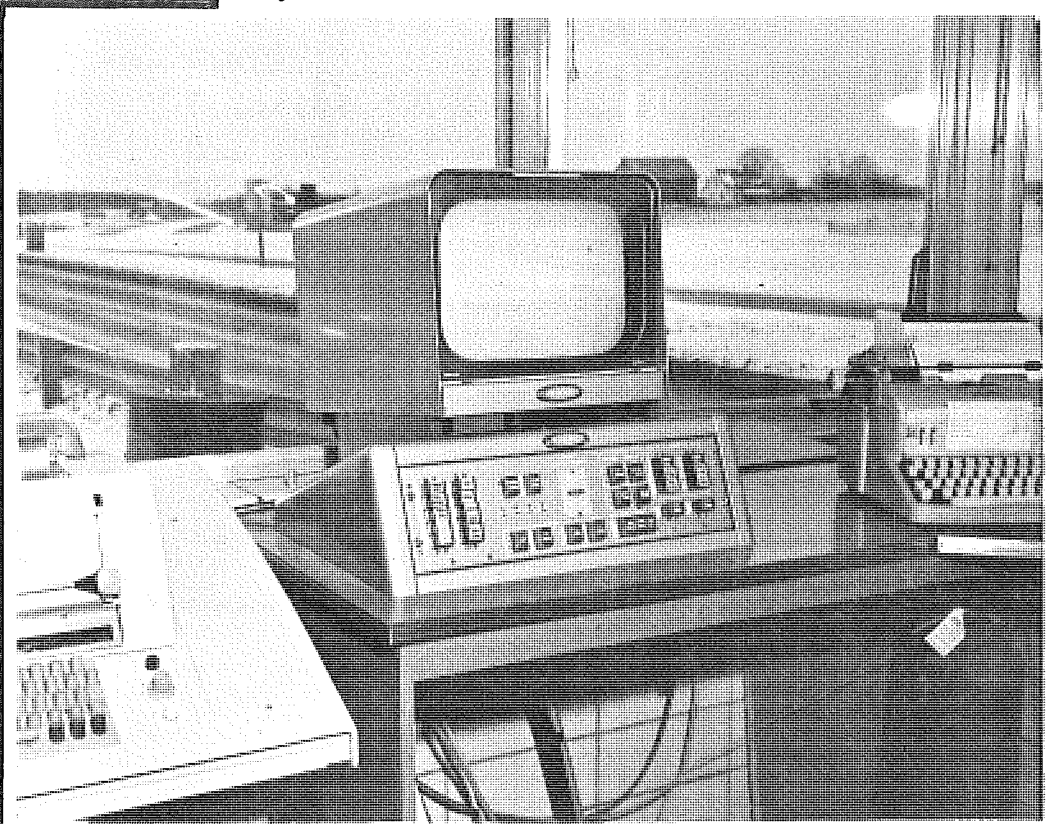
Now backing up to the point of exit from the evaluation path, and assuming the computer found the vehicle legal the overhead sign would direct it to the bypass lane.

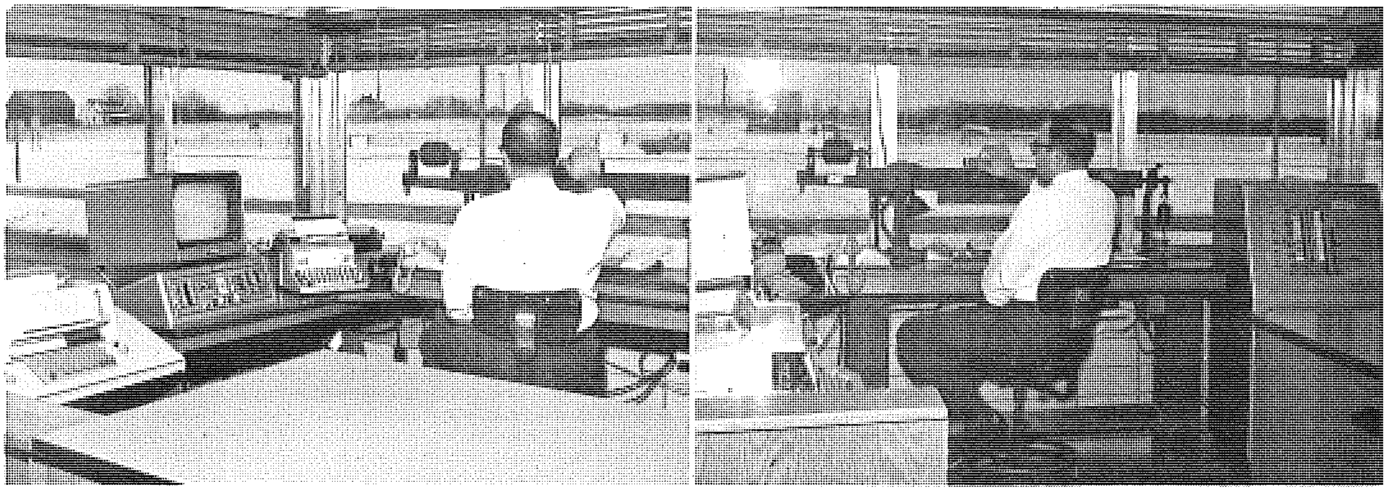


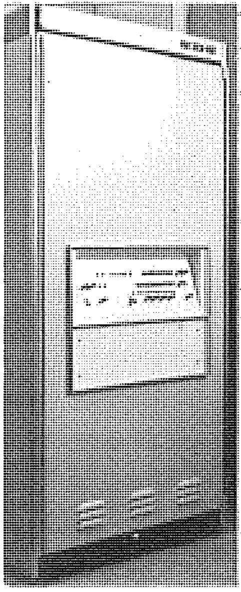


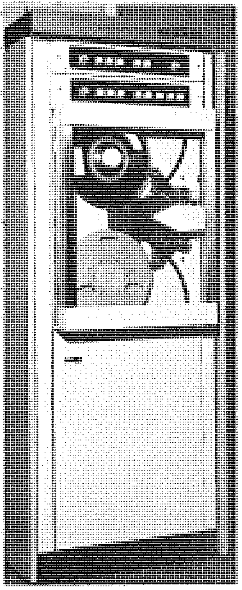
Television camera housing in place atop 26 ft tower. Housing contains two cameras; each focused on a different part of the evaluation path. Controls for the wiper, the individual camera irises and the night lighting are all on the weighmaster's console.

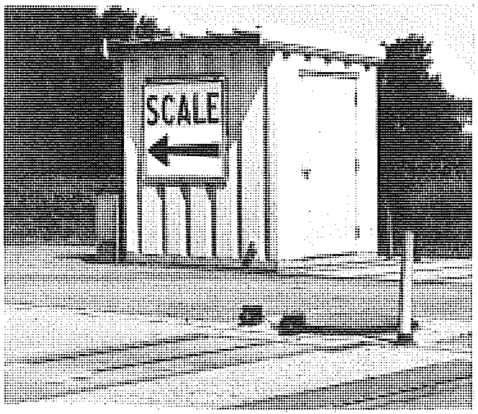
Here the monitor is shown mounted atop the weighmaster's console, providing the operator a split image (upper and lower screen) view of the site. The upper image shows the entire evaluation path. The lower image has been positioned so that a vehicle in violation (weight or dimension) will be displayed just after the computer sounds the audible alarm in the console telling the operator that a violator is approaching.



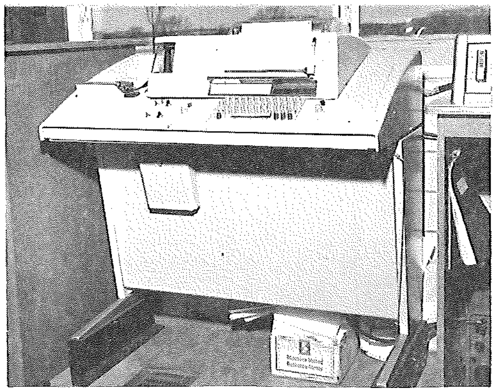

Two views of weighstation operator showing his normal operating position with respect to system instruments, teleprinter, weighmaster's console and TV monitor to his left, and survey console to his right. Computer, tape recorder and speed and classification console are in separate room at rear of scalehouse.

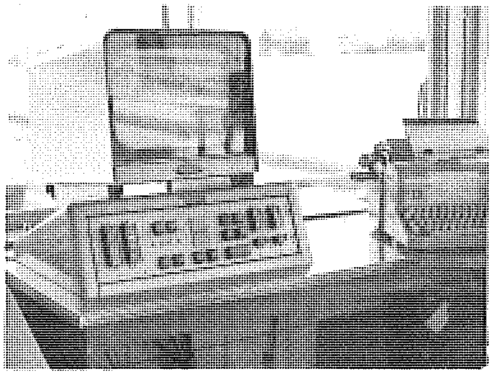

Computer

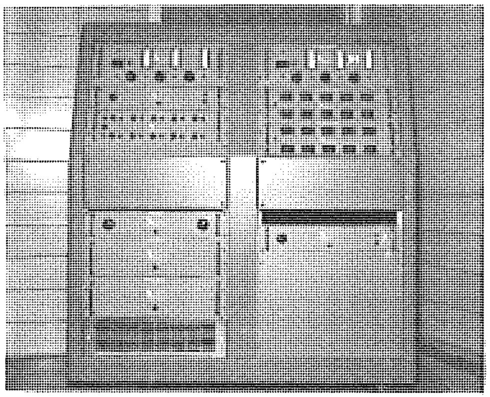

Tape Recorder

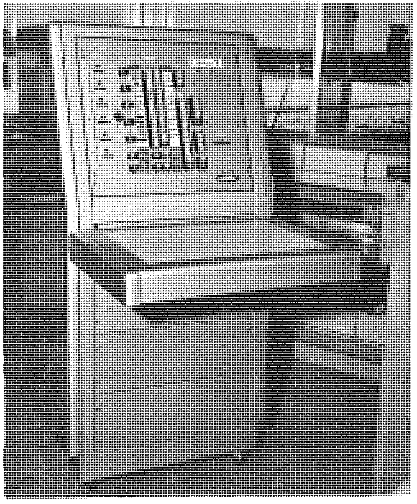


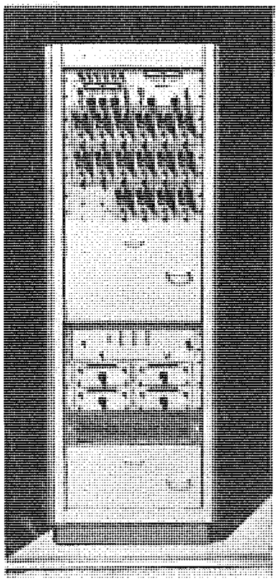
Shoulder enclosure building used as a terminus for all signal and power cables; as a system test and calibration center; and for storage of the myriad materials, tools, etc. necessary to a project such as this (future systems-non-prototypes would not require this component .


Teleprinter

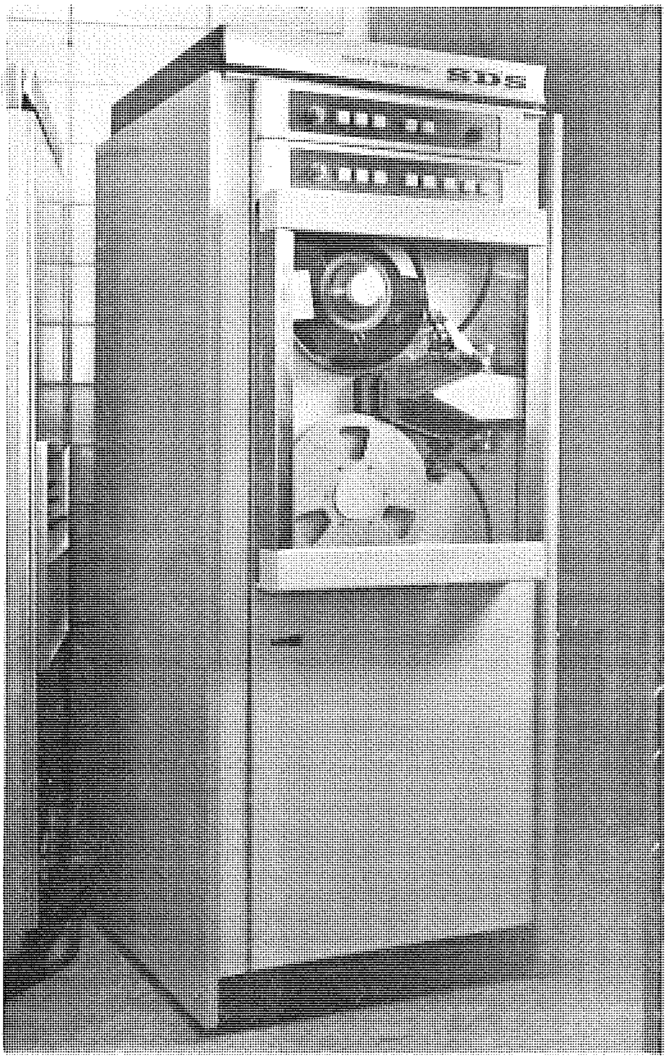

Television monitor atop weighmaster's console.

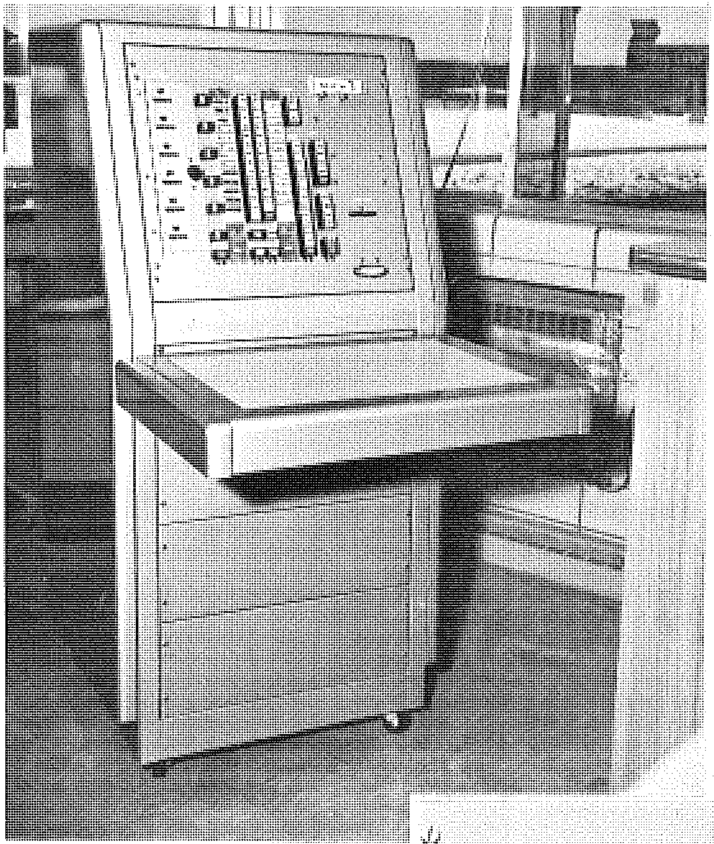

Speed and classification console


Survey mode console

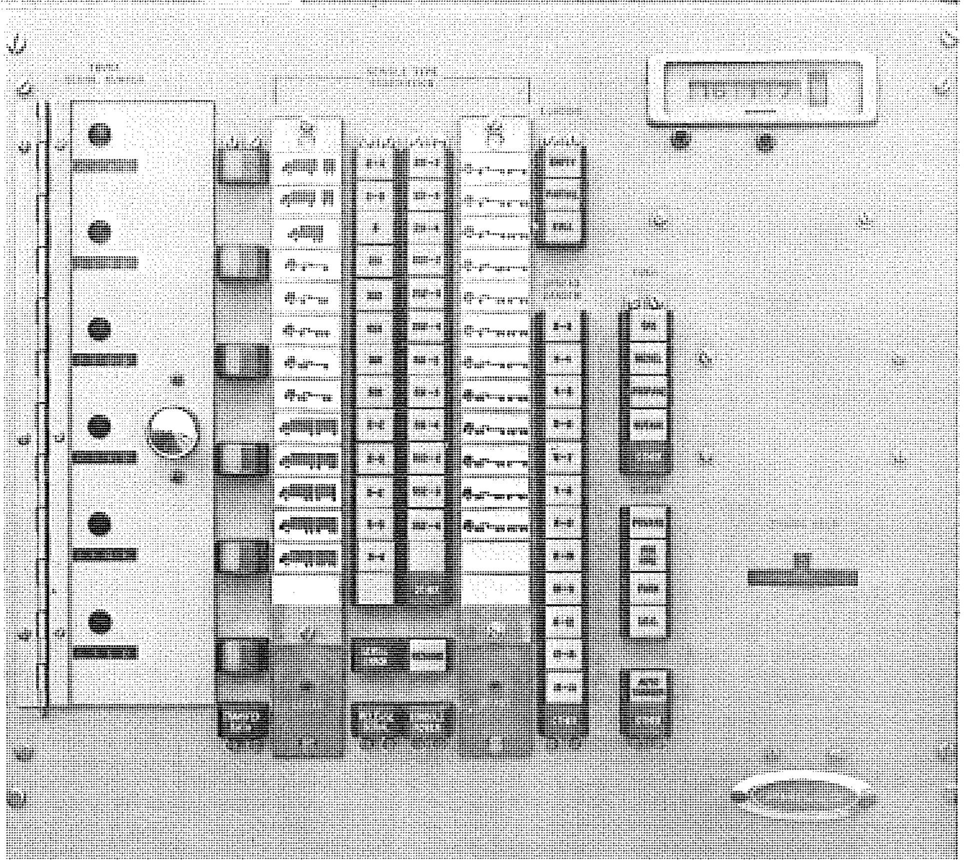

Pre-processor located in shoulder enclosure adjacent to evaluation path 1300 ft from weigh station.

Digital magnetic tape recorder for storing survey data.

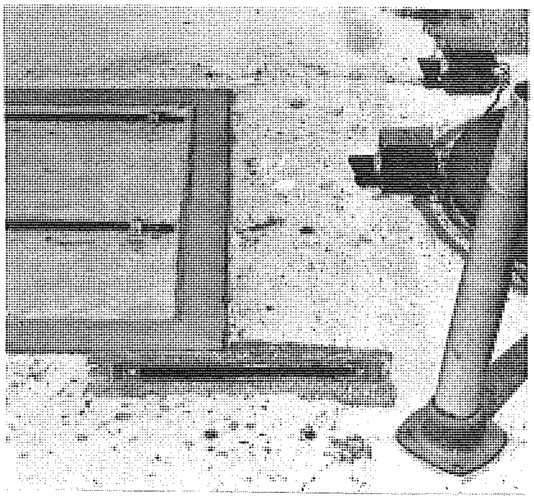




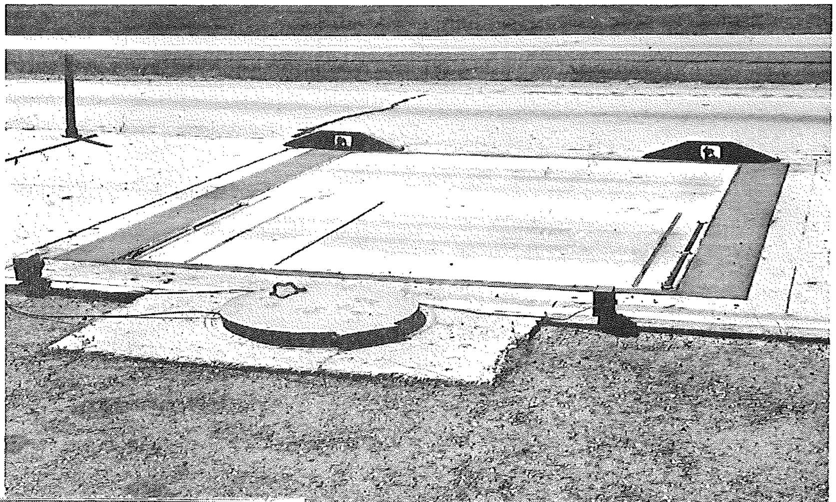
Survey console in weigh station.



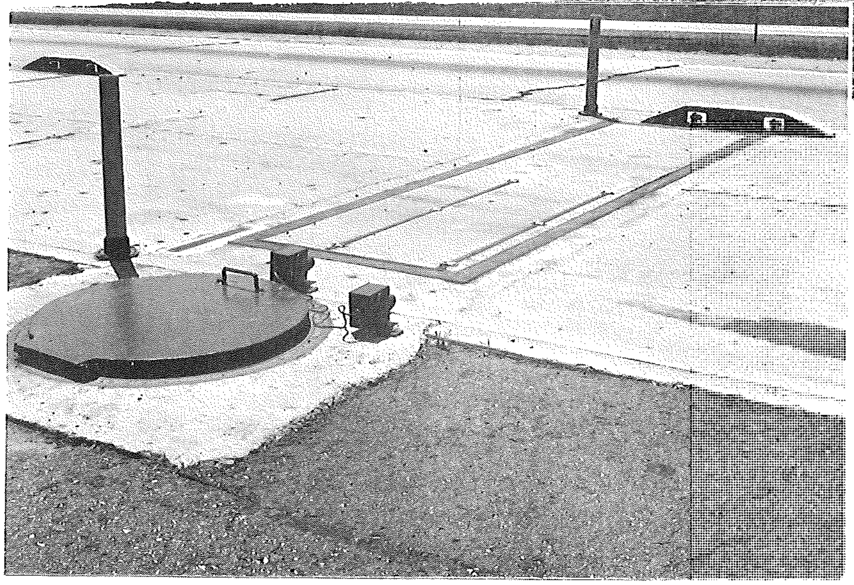
Manually operated keyboard of survey console for inputting vehicle data and serial numbers, and then with the "Transfer Data" key, transferring the information to the magnetic tape record.



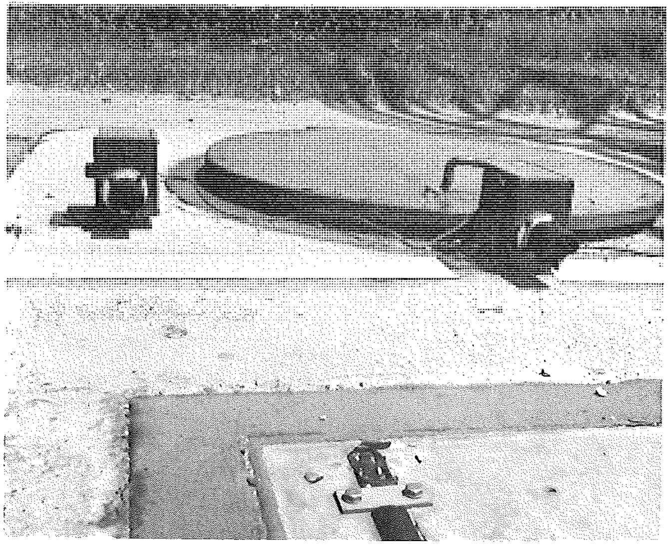
Embedded strip switch (mechanically actuated) which signals computer that a vehicle is not fully on-scale and therefore weights are invalid. Computer responds by routing such vehicle to mechanical scale for static weighing. One such switch is installed ahead of each scale.

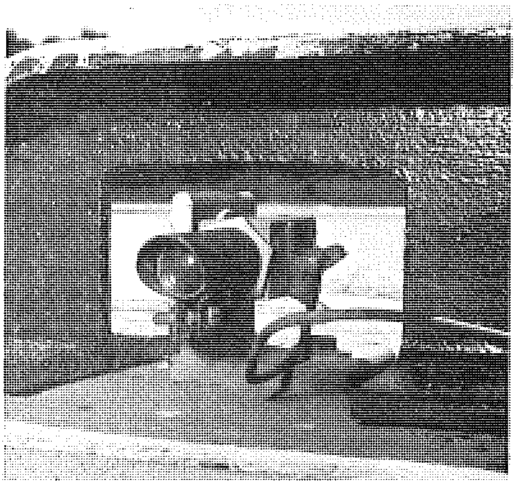


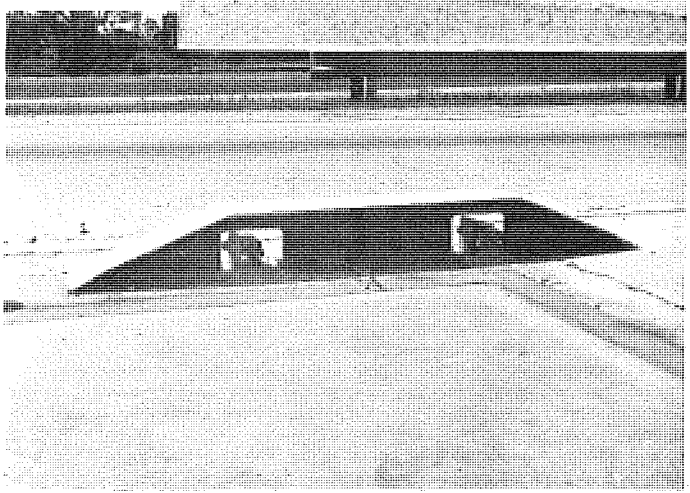
Photoswitch signalling entry and exit of axles to large scale platform and to one of small scale platforms.



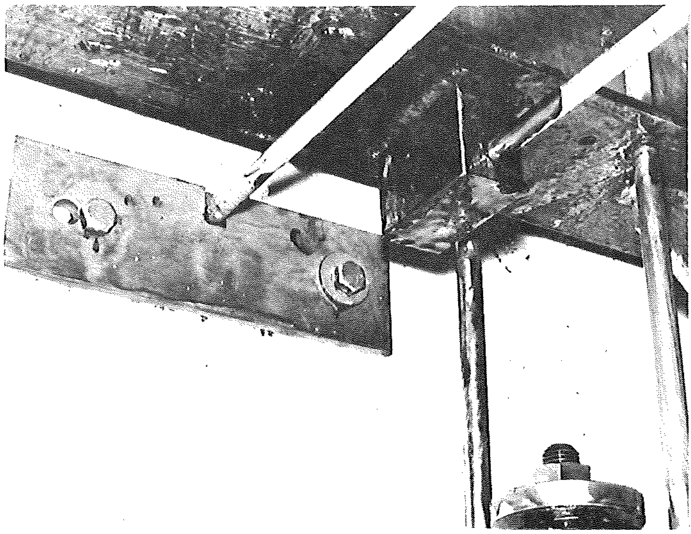
Closeup of two light source components of the photoswitches.



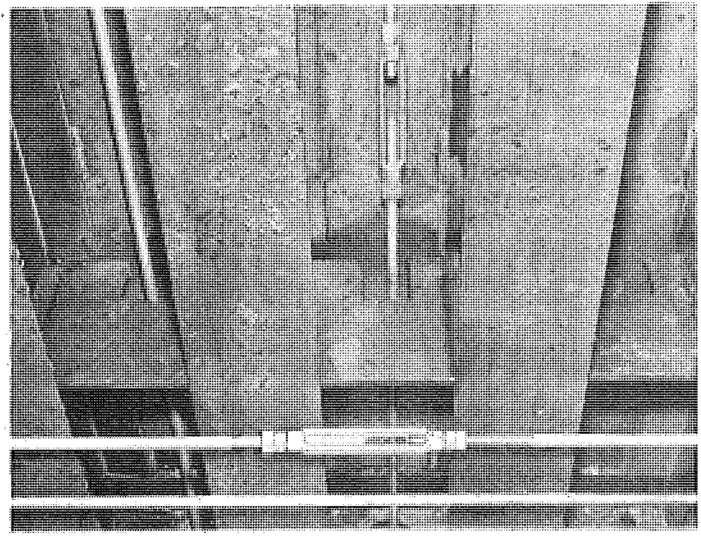




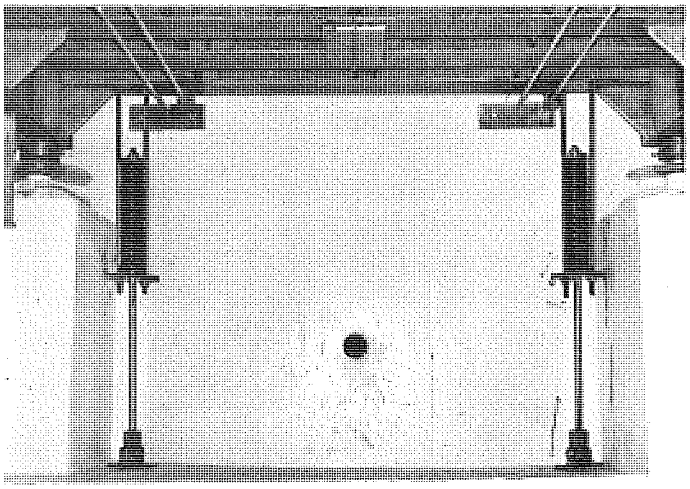
Two photo-detectors and a closeup of one, all under ramp-shaped, steel protective covers.



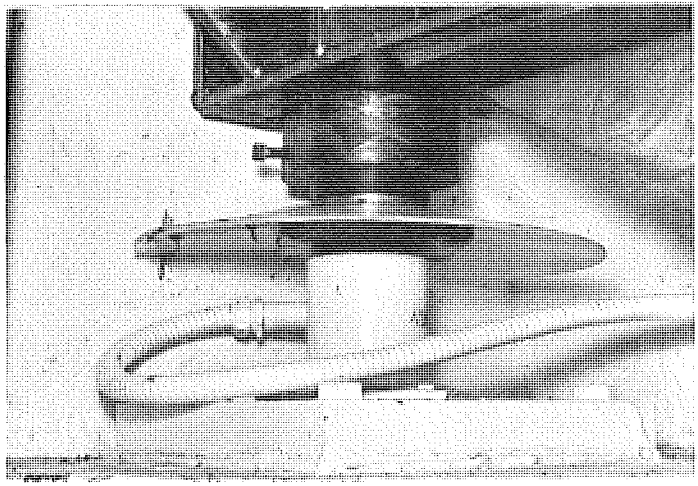
Closeup of check rod mounting. Rod at left is anchored to wall and its opposite end is fastened to opposite side of platform in the same manner as the rod at right - the right rods opposite end is anchored to wall on opposite side of pit.



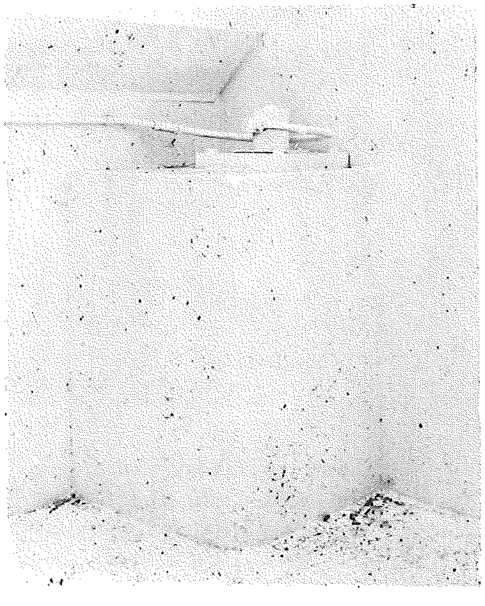
Looking up into bottom of large scale platform - longitudinal check rods can be seen up within platform while transverse rods are below - turnbuckles are used to position platform and then tightened (3000 lbs. tension) to secure it.



Inside large scale pit after installation of platform-preload springs, load cells and transverse check rods are visible.

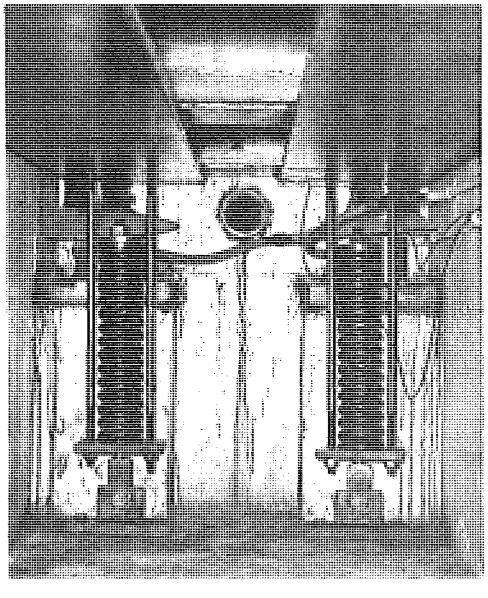


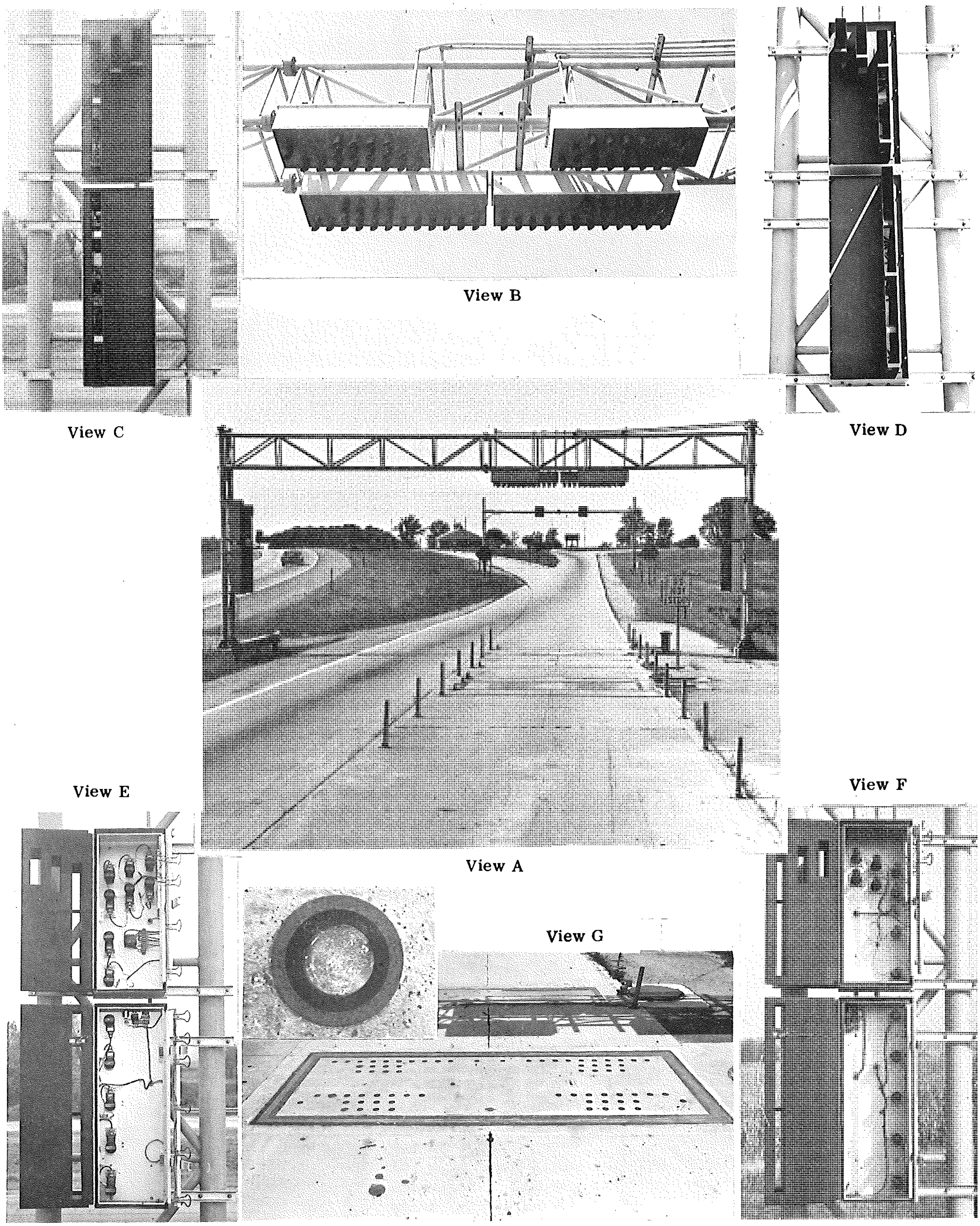
Closeup of load cell installation at one corner of large scale - from bottom up, the cell bearing plate, the load cell, dripshield, leveling screw jack, and bottom flange of platform beam.



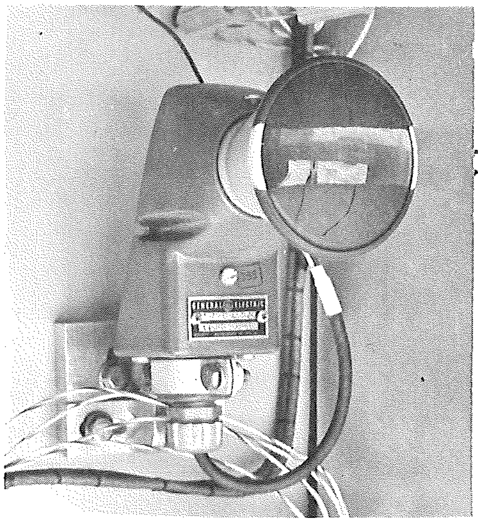
View of load cell on bearing plate atop concrete pillar in large scale pit -- somewhat obscured by white epoxy paint.

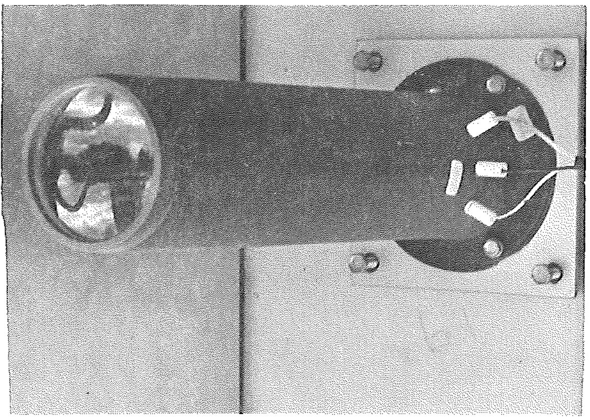
View into end of one small scale pit - all preload, transverse and longitudinal checks and load cell mounts are identical as in large scale except that all anchor rods are up within platform.



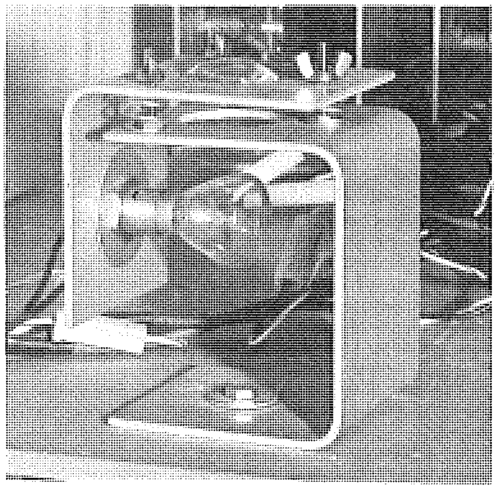


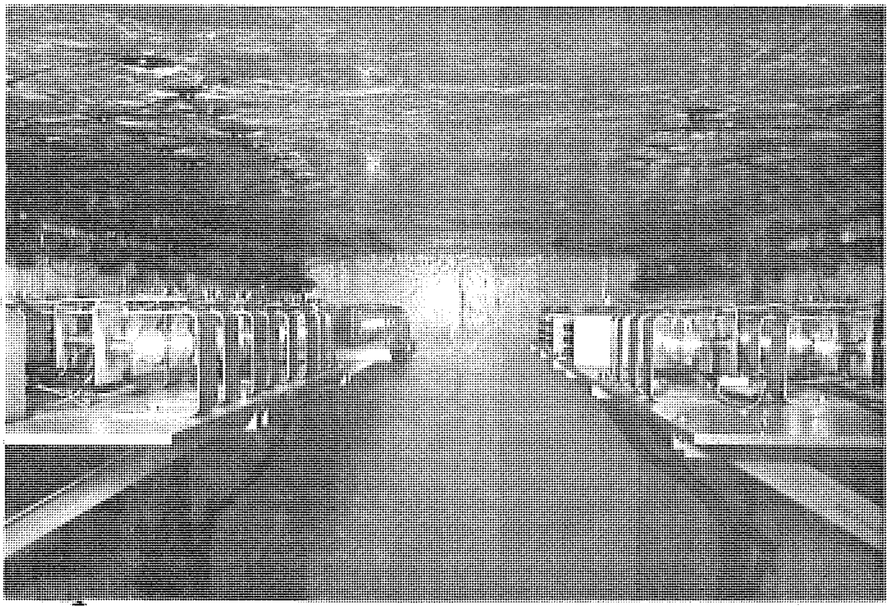
View A (center) shows the dimension truss as a vehicle operator sees it. View B shows the enclosures housing the 72 width and length detectors. Views C and D shows the height source and detector enclosures, while Views E and F show both enclosures with their protecting hinged covers open to show the source and detector units. View G shows the width and length light source parts in the cover of the pit containing the 72 light sources (inset closeup of port window).





Closeup view of height beam light source (left) and detector (right).

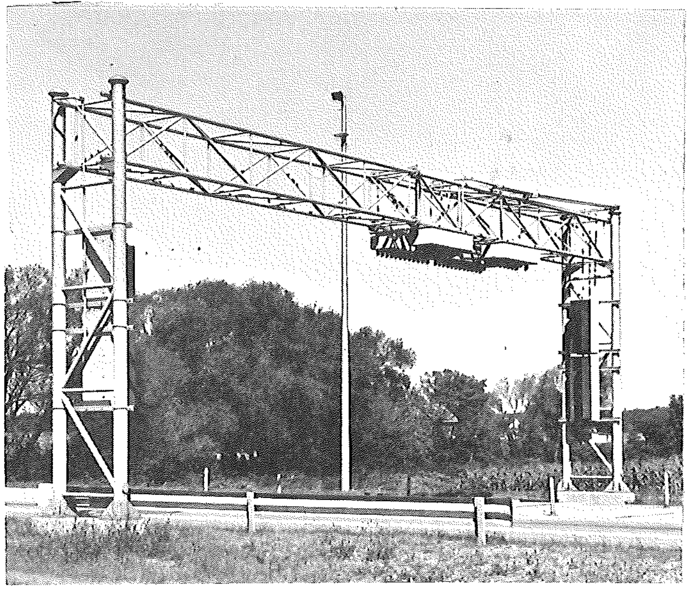




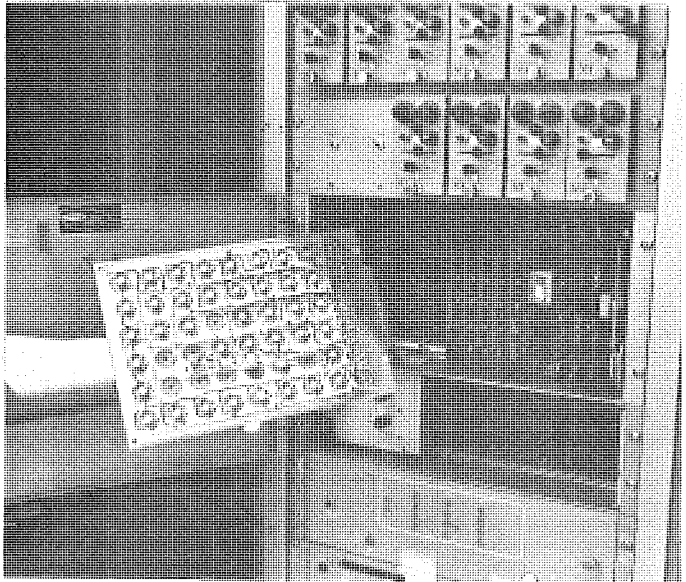
Closeup of one of the pit light sources shown in array at right.

72 light sources for width and length beams as mounted in pit under concrete cover. Bottoms of steel tube light ports are visible in underside of pit cover. Ports contain frost preventative heaters - wiring is visible.

View of dimension system truss as seen by westbound I 94 traffic.



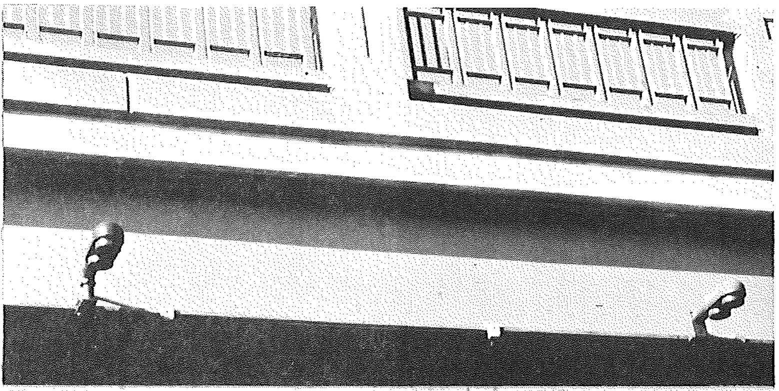
Dimension beam electronics, flip-flops, threshold adjustments and encoders (all contained in the Pre-processor located in the shoulder enclosure building).

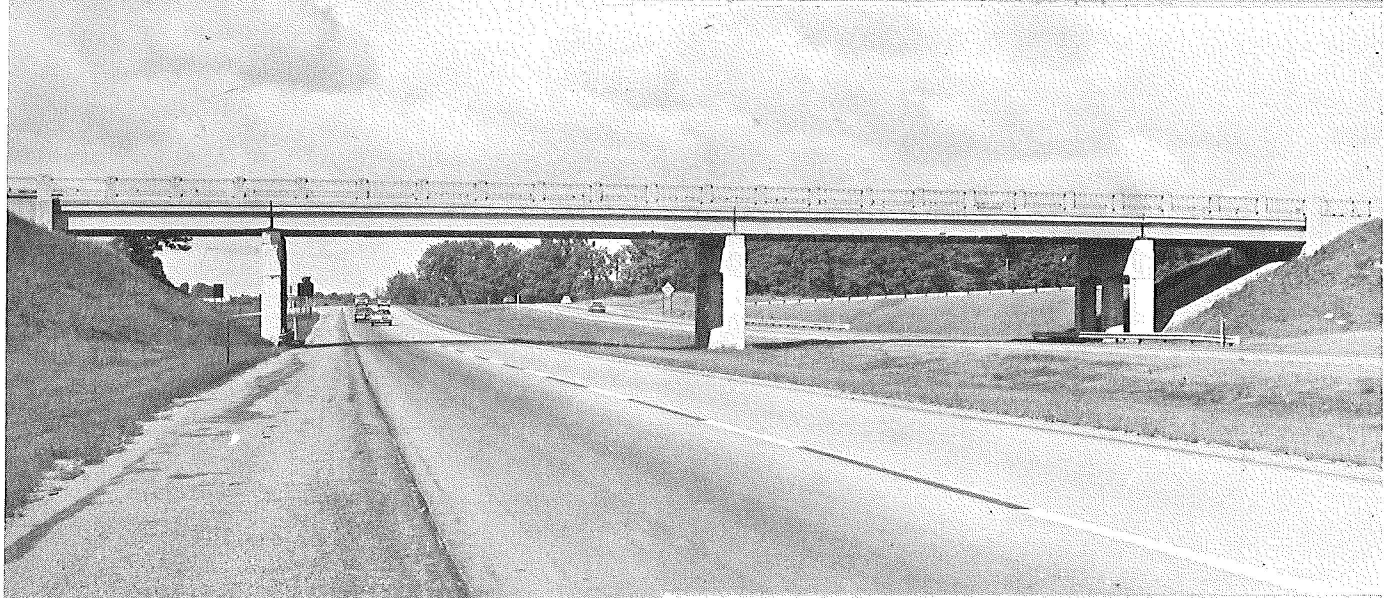


VEHICLE SPEED AND CLASSIFICATION SYSTEM
BY GENERAL RAILWAY SIGNAL CO.

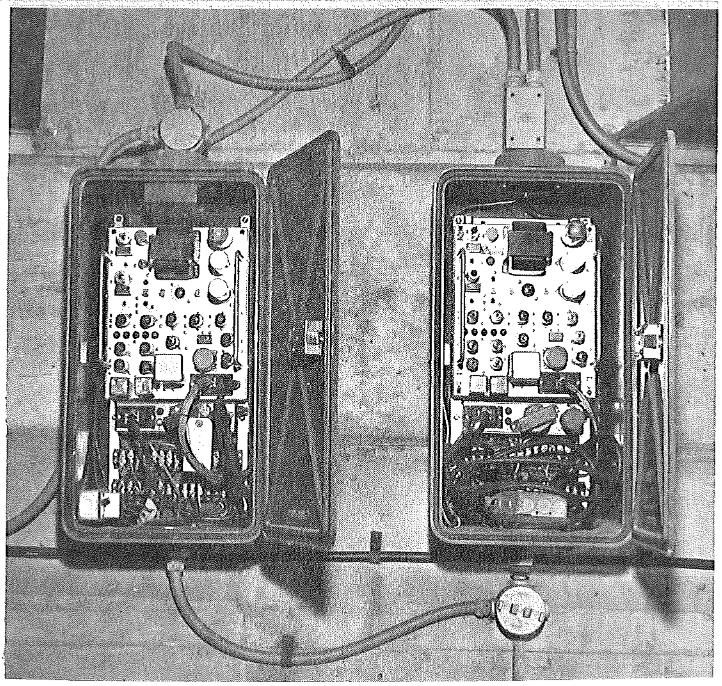
(Installed at Grass Lake weigh station during Part A)

View of transceivers mounted on approach underside of bridge over both traffic and passing lanes measuring vehicle height and thereby "car" or "truck." An identical pair measuring speed are mounted on leaving underside.

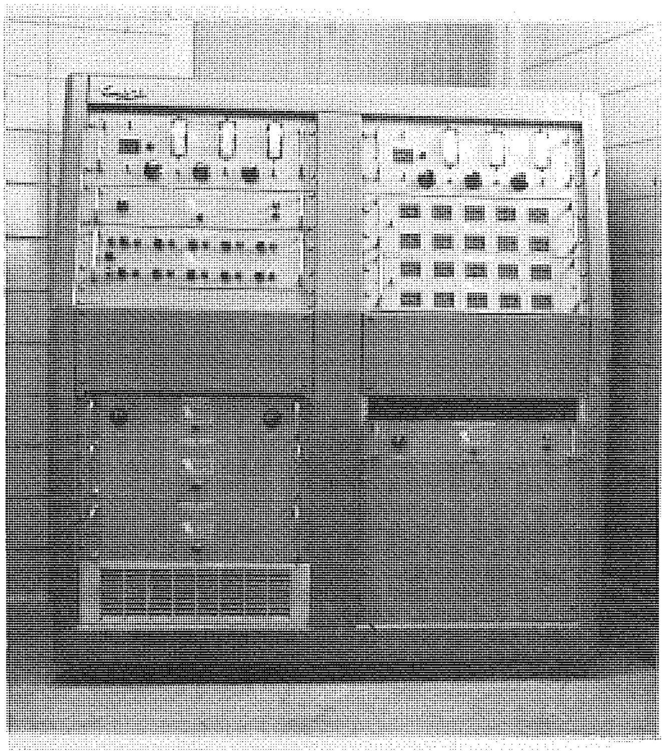




Mt. Hope Rd bridge over I 94 with speed and classification transceivers mounted over westbound I 94 lanes.

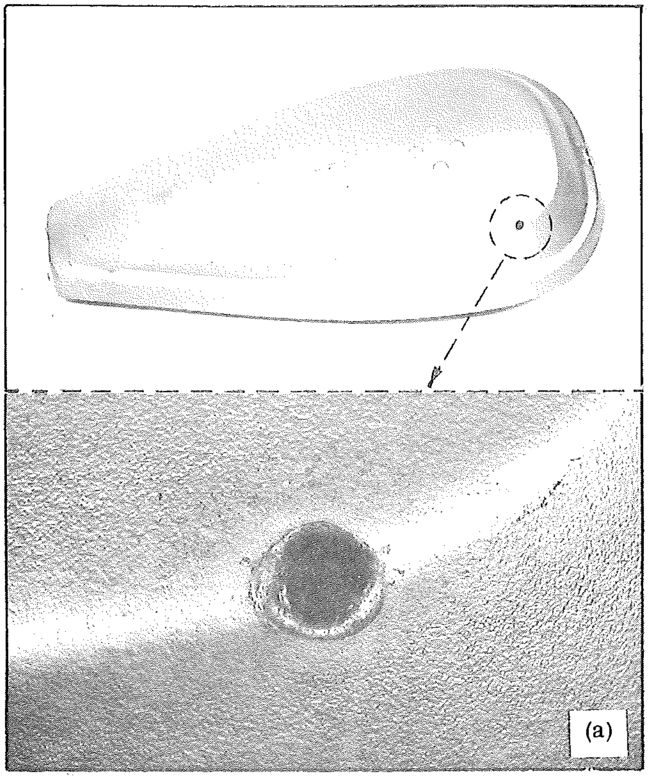


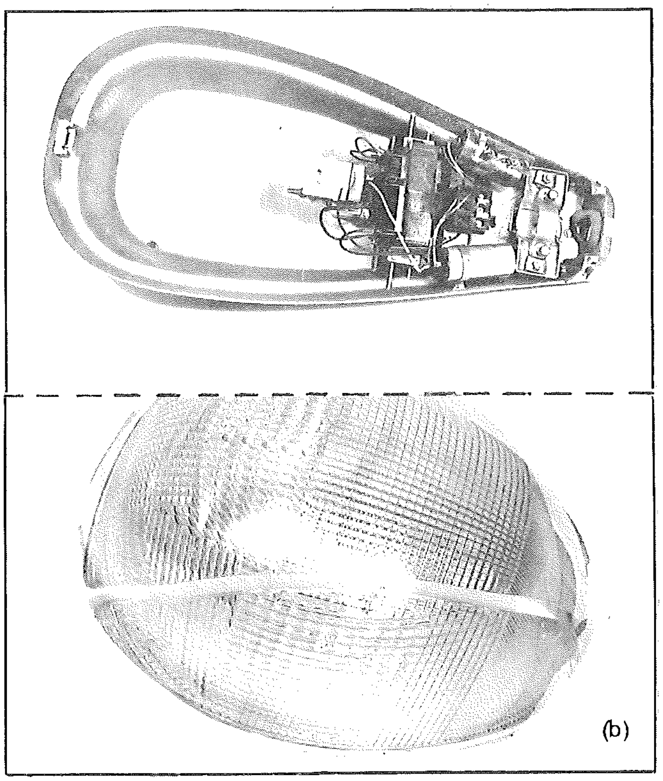
Electronic enclosures mounted on bridge abutment - containing signal generators, timing circuits, amplifiers, cable drivers, etc.

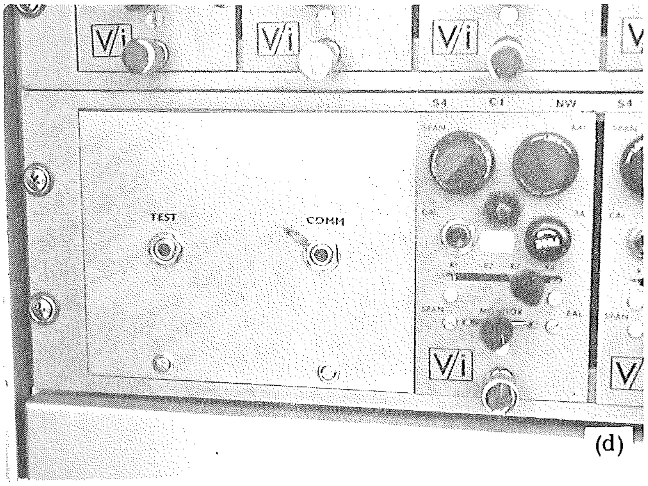


Recording and display console in weigh station 1-1/2 miles east of transceiver bridge installation.

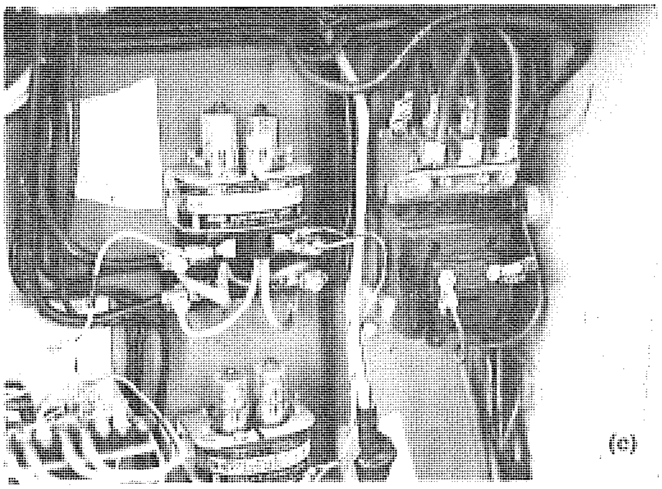
LIGHTNING DAMAGE

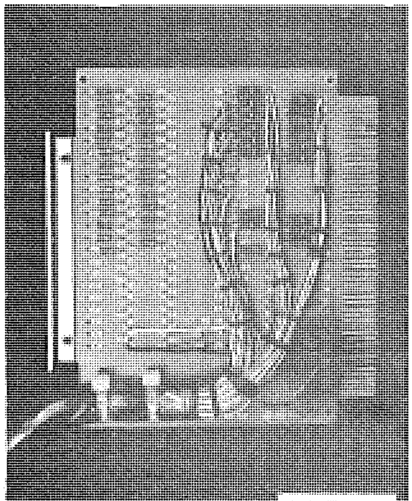

(a)

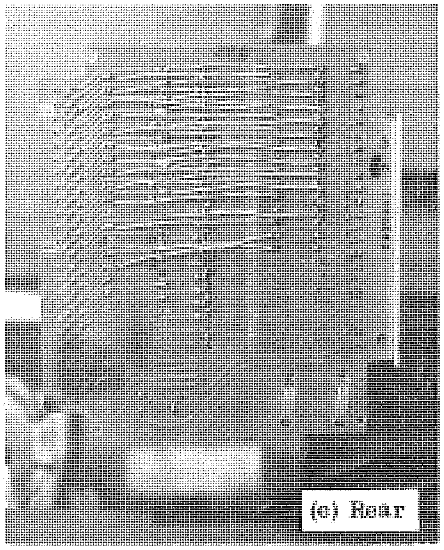

(b)



(d)


(c)


(e) Front


(e) Rear

The following is a best estimate reconstruction of the sequence of events during the first and most damaging of the many lightning strikes sustained by the system: (a) lightning bolt strikes the poorly grounded luminaire case, (b) lens fractures, charge enters luminaire power wiring, (c) jumps open contactor and enters power supply wiring of pre-processor, (d) surging through this unit it enters signal wiring, travels the 1300 ft to the weigh station where (e) it enters the computer junction box and spreads throughout computer, to tape, recorder, to teleprinter and weighmaster's console.