



COMMONWEALTH OF KENTUCKY
DEPARTMENT OF HIGHWAYS
FRANKFORT

HENRY WARD
COMMISSIONER OF HIGHWAYS

October 30, 1964

ADDRESS REPLY TO
DEPARTMENT OF HIGHWAYS
MATERIALS RESEARCH LABORATORY
132 GRAHAM AVENUE
LEXINGTON 29, KENTUCKY

H.1.61.27

MEMORANDUM

TO: W. B. Drake, Assistant State Highway Engineer
Chairman, Kentucky Highway Research Committee

SUBJECT: Research Report, "Weighing Vehicles in Motion";
KYHPR-61-27, HPS-HPR-1(25), Part II

The report, submitted herewith, consummates a significant phase of research dedicated to the development of a method for automatically counting and weighing vehicles in a normal stream of traffic. This report was prepared by the Department of Civil Engineering at the University of Kentucky acting under contractual arrangements with the Department and is a summary of the significant findings emanating from the study since its inception in 1961. The principal effort has been directed toward the development of an appropriate platform which might be installed in a pavement. The sensing elements have been considered to be within the scope of this project; however, the apparatus for recording and processing the out-put data has not been considered to be a specific part of the work consigned to the project team because a similar project in Michigan is devoted principally to the development of a system for monitoring and analyzing such data. In a sense, each project compliments the other.

At the outset, it seemed essential not only to accurately sense and measure the instantaneous, dynamic axle-loading but also to develop a method for determining the actual, static weights of the respective axles. During the progress of this work, these concepts have changed; static axle-weights are now considered to be essential only from the standpoint of enforcing legal load-limits; whereas, dynamic loading may be considered as being the more realistic value from the standpoint of the behavior of pavements. Correlations between the two types of measurements have been sought, and the results obtained thus far are encouraging. However, it does not seem necessary to await the ultimate refinement of dynamic-to-static corre-



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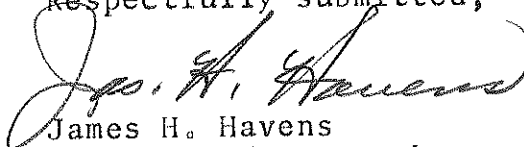
lations before the load-recording systems can be put into actual service or yield valuable data. These viewpoints in no way compromise the original objectives or the ultimate plan which envisions the automatic counting and measurement of traffic loadings--for planning and research purposes.

Since the receipt of this report, this project has been continued under HPS-HPR-1(26), which covers the current fiscal year--looking toward the implementation of an operational installation during the succeeding year.

Four copies of this report were submitted to the Bureau of Public Roads May 11, 1964. Following their review, they suggested that a minimum of 60 copies be printed and made available to each state. We are complying with this suggestion.

Comments and suggestions are invited.

Respectfully submitted,



James H. Havens
Director of Research
Secretary
Kentucky Highway Research Committee

JHH:skb

cc: Research Committee
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Research Report

WEIGHING VEHICLES IN MOTION

A Summary Report
Project KYHPR-61-27; HPS-HPR-1(25)

Prepared By

Department of Civil Engineering
COLLEGE OF ENGINEERING
University of Kentucky

for

Division of Research
DEPARTMENT OF HIGHWAYS
Commonwealth of Kentucky

in cooperation with the

BUREAU OF PUBLIC ROADS
U.S. Department of Commerce

April 1964



WEIGHING VEHICLES IN MOTION

A SUMMARY REPORT

HPS 1 (22)

KRF 3359

APRIL 1964

**DEPARTMENT OF CIVIL ENGINEERING
UNIVERSITY OF KENTUCKY
LEXINGTON, KENTUCKY**



ABSTRACT

This report describes the construction, installation, testing and performance analysis of three types of dynamic electronic scales; the Tallar-Cooper, a commercially developed four load cell scale, the Broken Bridge, an adaptation of a German prototype employing two load cells and the Beam Type Scale, an experimental prototype that uses a pair of instrumented aluminum beams as the weight sensors.

Chapters I, II and III of the report include detailed descriptions of the scales, the test sites and the testing program. Chapter IV is an analysis of the effect of various factors such as crossing speed, preload (application of a vertical stabilizing force), axle position, approach smoothness and other site conditions on the performance characteristics of the three scales. Basis of comparison is the deviation of the dynamic axle weight as measured by each scale from the pre-determined static axle weight. Several graphical and statistical illustrations are used to validate the comparisons.

The conclusions reached in Chapter V may be summarized as follows:

- (1) All three scales will accurately measure the applied load.
- (2) Each scale will perform satisfactorily in the applications for which it is best suited. These were determined to be:
 - (a) For the collection of highway planning and economic data - the Broken Bridge and the Beam Scale
 - (b) For the collection of data to be used in pavement design - the Broken Bridge and the Beam Scale
 - (c) For research in pavement and vehicle dynamics - the Tallar-Cooper scale.
 - (d) For the collection of statistical axle load data - all three scales.
 - (e) To aid in the enforcement of axle weight limitations - all three scales.
- (3) The most important use of the dynamic scale is in the measurement of forces applied to the highway surface by the axles of a moving vehicle.

The appendices include: (1) a comprehensive bibliography with synopses of some of the more pertinent entries, (2) details of some corollary experimentation in strain gage waterproofing and the use of an epoxy-sand mortar approach surfacing, (3) an outline of the data

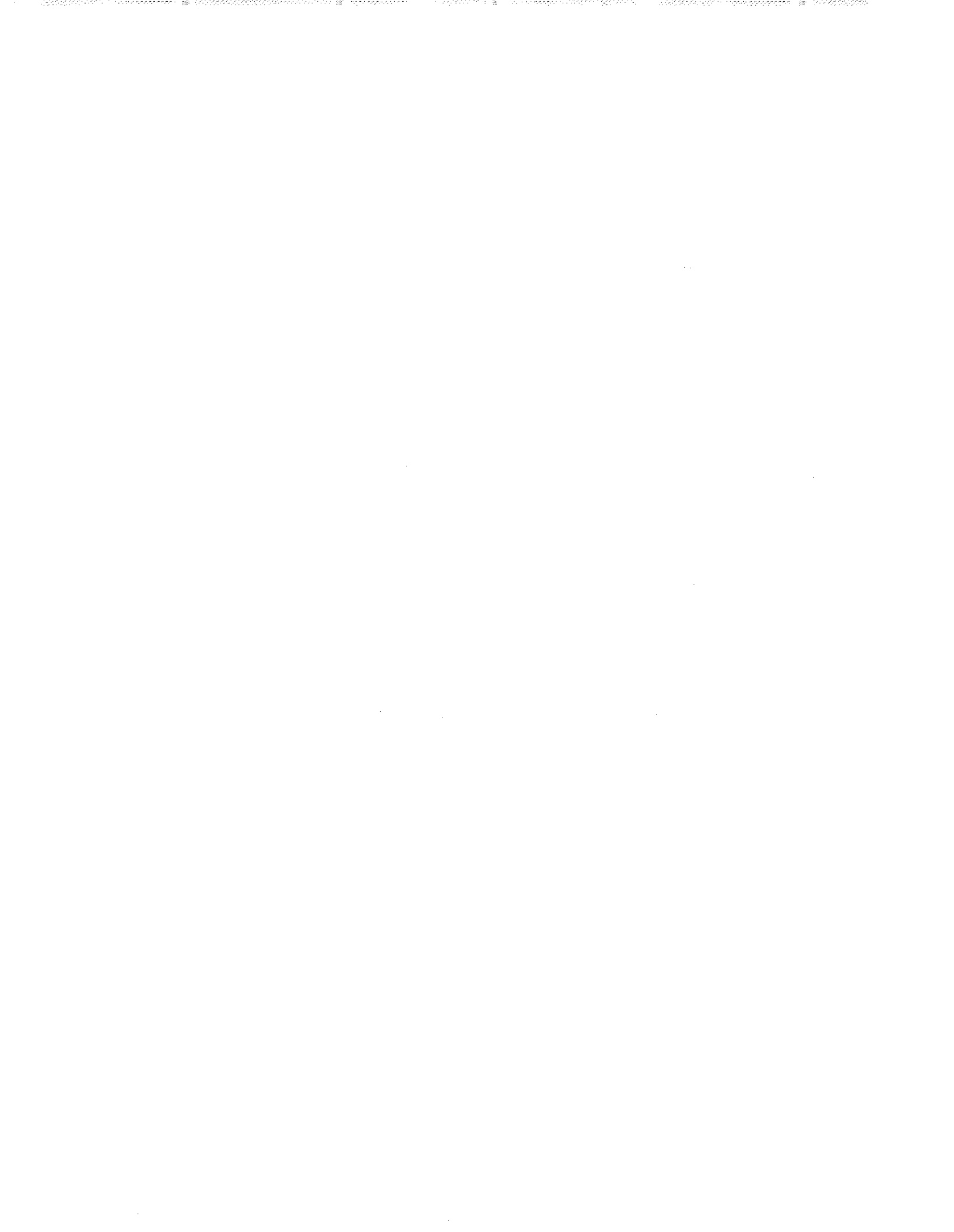


Abstract (continued)

collection instrumentation, (4) excerpts from two theoretical studies of the Broken Bridge scale and preloading, (5) a description of the procedures used to prove that the scales were actually measuring the applied loads and, (6) tabular summaries of statistical data resulting from the analysis of the dynamic axle weights of trucks diverted from the normal traffic on an Interstate highway.

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CHAPTER I

INTRODUCTION

General

The need for a dependable method of weighing the axle loads of a moving vehicle has long been recognized by those agencies and individuals concerned with the planning and operation of our highway system. Present methods of collecting wheel load data and detecting overloaded trucks are slow and costly. An efficient dynamic weighing system in continuous operation would provide a complete record of the loads applied to a roadway over a long period of time, thereby facilitating performance studies and opening the way for future design improvements. With proper instrumentation the system could also be made to yield the volume, speed and axle spacing data needed in such work.

When installed in the roadway ahead of a conventional enforcement weighing station the dynamic scale could be used to detect and divert from the traffic stream (by an automatic sign) only those vehicles suspected of being loaded beyond the legal limit. Lightly loaded or empty vehicles would be permitted to proceed without being needlessly stopped for weighing.

Previous Research and Development

The electronic scale, originally developed for static weighing, has been the basic component of practically all dynamic weighing installations constructed thus far. The electronic scale consists of a platform supported on strain gage load cells. An applied load is

measured by the amount of strain it produces in the short steel columns which make up the load cells. The strain is detected by resistance wire strain gages bonded to the columns (Figure 1). The gage output is amplified and translated into an indication of weight, usually through a recording oscillograph (9, 10, 14, 15)*. Figure 2 shows a typical dynamic weighing installation.

Experimental work in dynamic weighing was pioneered by the Bureau of Public Roads in 1951 (16). Using a load cell-supported concrete platform and an electronic apparatus designed for weighing aircraft, the Bureau engineers ran an extensive series of tests, weighing various types of vehicles at speeds up to 50 mph. Significant results of these tests were that:

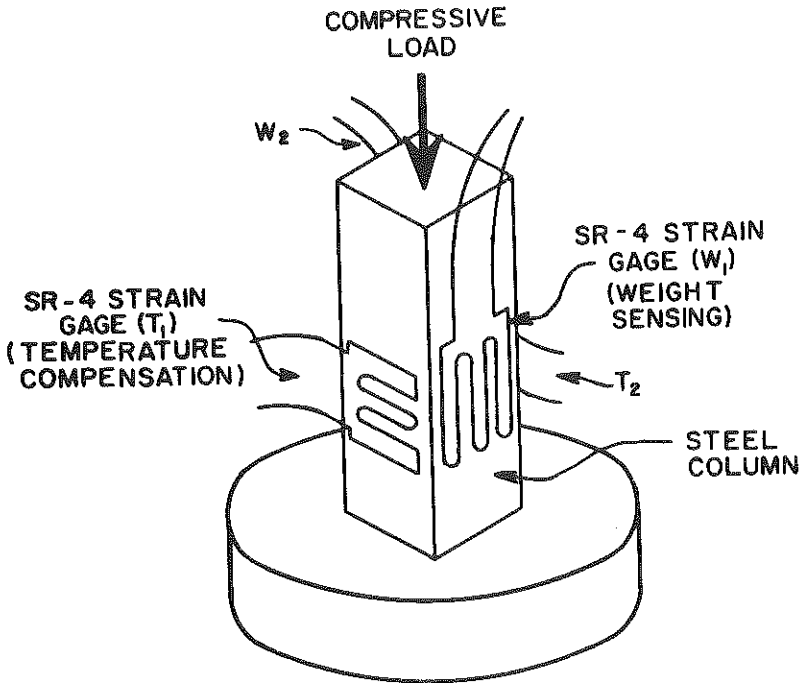
(1) the vehicle's undulations caused the dynamic weight to vary above and below the static weight in a random manner,

(2) the dynamic weight of the second axle of a tandem differed greatly from the static because of residual platform vibrations induced by the first axle (preloading the platform with vertical tie bolts reduced this error) and

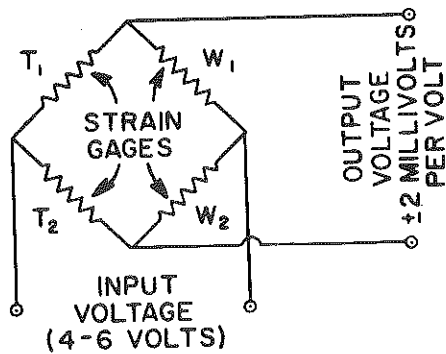
(3) the gross weight of a large number of axles could be obtained with a relatively high degree of accuracy due to the canceling-out effect of the random variations between dynamic and static weights.

An improved version of the Bureau's original scale was used to study methods of measuring variations in the loads applied to the pavement by a moving vehicle (31). This research confirmed the fact that the electronic scale measures the actual force exerted by the wheels as

* Numbers refer to items listed in the Bibliography, Appendix A.

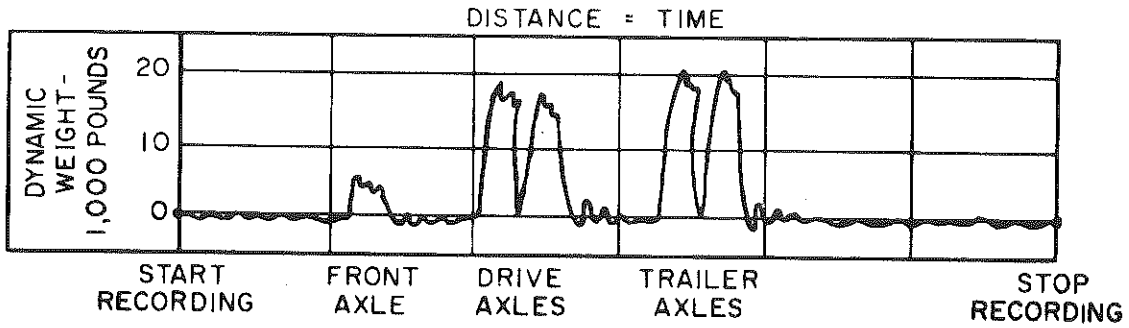


LOAD CELL - SCHEMATIC DIAGRAM



TYPICAL LOAD CELL CIRCUIT

FIGURE I. - THE STRAIN GAGE LOAD CELL



TYPICAL OSCILLOGRAPH RECORDING
(5-AXLE TRUCK - TRAILER)

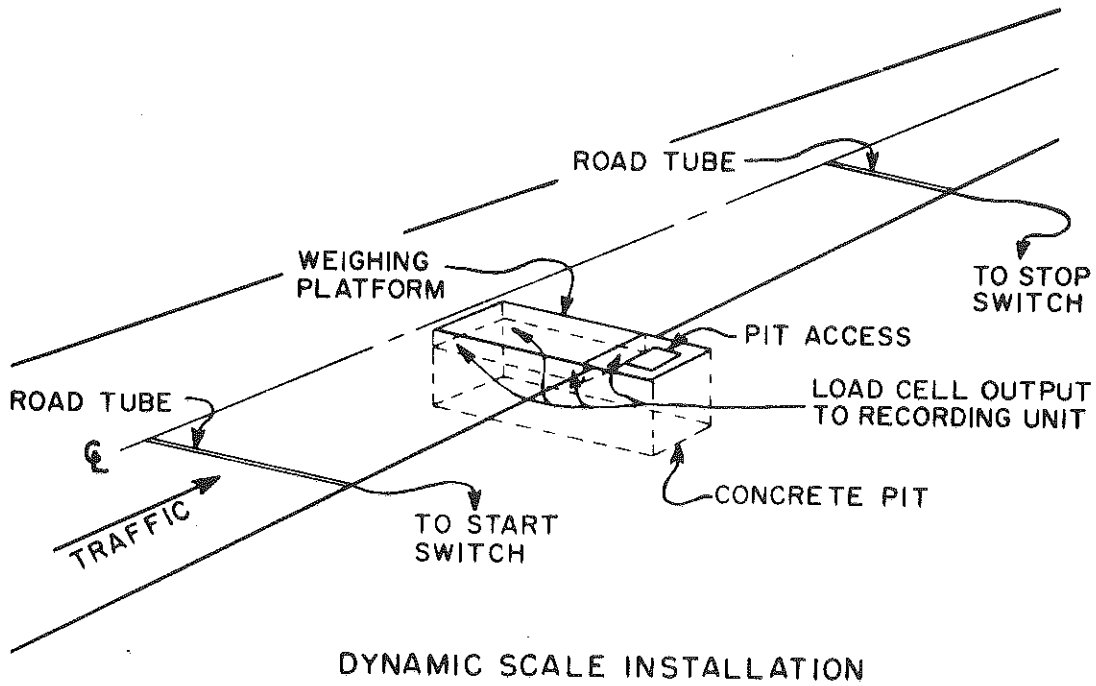


FIGURE 2. - HIGHWAY INSTALLATION OF A
DYNAMIC WEIGHING SCALE

the vehicle passes over the platform - a force that varies from the static weight by an amount which depends upon the amplitude and frequency of the vehicle's undulations.

Encouraged by the results of the Bureau's experimental work, a few electronics firms began manufacturing scales for dynamic weighing. Several of these commercial scales were installed in the Highway systems of Iowa, Minnesota, Oregon and Indiana.

The State of Iowa used the dynamic scale exclusively in the collection of highway planning data. Their experience with the device has been very satisfactory. Iowa plans to eventually replace their loadometer cross with a system of dynamic scales utilizing a mobile instrument van. (29).

Minnesota has used the scale for both overload detection and data collection (36). Maintenance problems have been few.

Many difficulties were encountered during Oregon's attempts at dynamic weighing. (37). Excessive moisture in the scale pits and electronic maintenance were the major items. This state abandoned extensive use of the electronic scale in 1958. (38).

Dynamic scales were used for experimental purposes at the AASHTO Test Facility in Illinois and at the Highway Research Laboratory in Michigan (39).

Development of a dynamic weighing device other than the floating platform electronic scale has been the subject of master's theses by students at the University of Kentucky (23) and Mississippi State University (22). The first investigated a method of detecting weight by the bending in a simple beam; the second designed and built a portable

scale using a series of small "hot wire" load cells. Preliminary testing showed both of the methods to be worthy of further investigation. A practical scale employing a short instrumented cantilever beam was developed in Sweden and is being used to collect road loading data in that country (46).

Some of the most promising advances in dynamic weighing have taken place in England and Germany. Here, the main interest is also in the collection of axle load data for planning purposes.

The British Road Research Laboratory has done some experimental work using a scale similar to those developed in this country (17). Their recording set-up however is quite different. By using a mirror galvanometer which deflects in proportion to the applied weight, a light beam is made to travel over a bank of eleven photoelectric cells; the greater the weight the greater the number of cells activated by the light. The photo cell output operates a mechanical register which records the axle load as falling into a definite weight class. Though the precision of these measurements is rather low (about 10%), the almost instantaneous response of the system permits continuous recording of all axle loads passing over the scale. Twelve of these units will be placed in operation on the British Road System during the next two years (1963-65).

A West German research organization has built a scale which features a "broken bridge" platform (18). The broken bridge consists of a steel platform split lengthwise into two sections of equal width. The outside edge of each section rests, near the corners, on a hinged support similar to a bridge rocker. The contiguous edges are supported,

through interlocking bearing plates, by two strain gage load cells. This unique design results in the weight being recorded by the oscillograph as the peak of a triangular pattern. The recording system used with the German scale classifies the axle loads into various weight groups. The original scale has been in operation near Stuttgart since 1958. Other installations are planned.

Since 1962, researchers of the Michigan State Highway Department have been conducting field tests of various traffic data collection devices and recording instruments, including a system of multiple dynamic scales (74). A final report on the first part of this project is expected in early 1964.

The continuing interest in the problems of dynamic weighing is exemplified by the fact that the National Cooperative Highway Research program is currently sponsoring an investigation which, it is hoped, will result in a system capable of determining the weight of a moving axle to within $\pm 5\%$ of the static value.

Purpose and Scope

This report describes the construction, installation, testing and performance analysis of three different types of dynamic scales.

The research was done by the Department of Civil Engineering, University of Kentucky in cooperation with the Kentucky Department of Highways and the Bureau of Public Roads*. The project was started in

* Principal Members of the Kentucky research team are: David K. Blythe, Civil Engineering Department Chairman, Project Director; John A. Dearing, Associate Professor of Civil Engineering, Assistant Project Director; Russell E. Puckett, Assistant Professor of Electrical Engineering, Instrumentations Engineer.

1960 for the purpose of determining the optimum mechanical configuration for a scale which would perform the dynamic axle weighing function in an overall data-gathering system. The development of the devices to acquire the dimensions, speed and the volume of passing vehicles and the design of the associated recording systems were assigned to the aforementioned Michigan project. A close liaison has been maintained between the Kentucky and Michigan research teams during the course of the work.

CHAPTER II

DESCRIPTION OF THE WEIGHING SYSTEMS

Investigation of the various types of transducers used for the measurement of weight (or deflections due to weight) showed that the commercially available load cell was best suited as the weight sensor of a dynamic scale. Two of the scales tested were equipped with these devices. It also seemed desirable to look into the possibility of developing a low-cost scale of simple design that could be operated in a relatively shallow pit. The beam-type scale was designed to meet these criteria.

The Broken Bridge Scale

The decision to build and test the broken bridge scale was prompted by a German report which describes the prototype in some detail (18). Desirable features of this scale were the V-shaped wave form produced by the two piece platform and the resistance to horizontal movement afforded by the hinged edges.

In the Kentucky version of the Broken Bridge the platform is made up of 15" channels welded securely together and covered with 3/8" thick skid plate. Each section is 2'-2" wide and 10'-0" long. Allowing for suitable clearance at all edges, the assembled scale measures 4'-6"x10'- $\frac{1}{2}$ ". The total weight is about 2000 pounds. The outer edges of the platform sections are supported on steel bridge rockers, each of which is equipped with two vertical pintles imbedded in the bottom half of the rocker and fitted snugly into holes drilled in the upper half. Contiguous platform edges are supported through pairs of heavy angles on two Type C, 50,000 pound capacity Baldwin-Lima-Hamilton Load Cells (Figure 3). A flat pitch screw mechanism

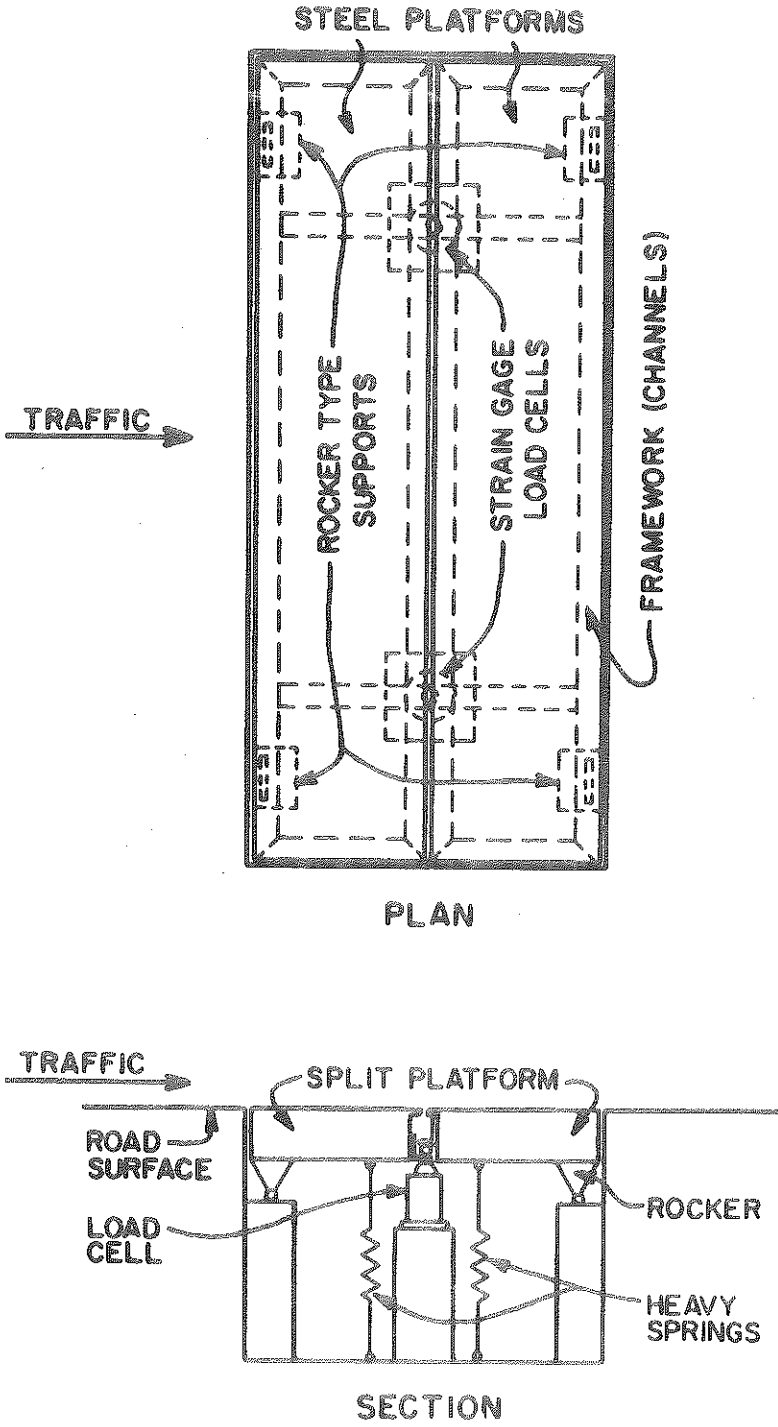


Figure 3. Schematic - The Broken Bridge Scale.

between the lower side of each angle and the load button of the cell provides a means of vertical adjustment in the center of the split platform (Figure 4). The rocker supports are adjusted vertically by shimming. Vertical stabilization and pre-loading of the platform was at first accomplished by steel rods and turnbuckles attached to the lower side of the platform and anchored in the pit floor (Figure 5). For reasons to be mentioned later in this report, the rods were eventually replaced with heavy coil springs similar to those used in the original German version (Figure 6).

The broken bridge scale as described above was subjected to a series of field tests at the University Farm Test Site and at the Interstate Highway 64 Site. The platform and its supports have remained structurally sound during this period (1961-1964) and the load cells have continued to function satisfactorily under widely varying weather and moisture conditions.

The Taller-Cooper Scale

In the first phase of the Kentucky project an attempt was made to investigate all previous developments in the field of dynamic weighing, both practical and experimental. This necessitated a number of inspection trips to existing scale sites and contacts with manufacturers of dynamic weighing systems. In recognition of the developmental research that is represented by a working commercial product, it was decided to include in the project's testing program a four load cell scale manufactured by the Taller-Cooper Division of the American Electronics Company, Inc. This scale was acquired in 1961 and consists of a 2'-8" x 10'-0" box-like steel platform supported near each corner by

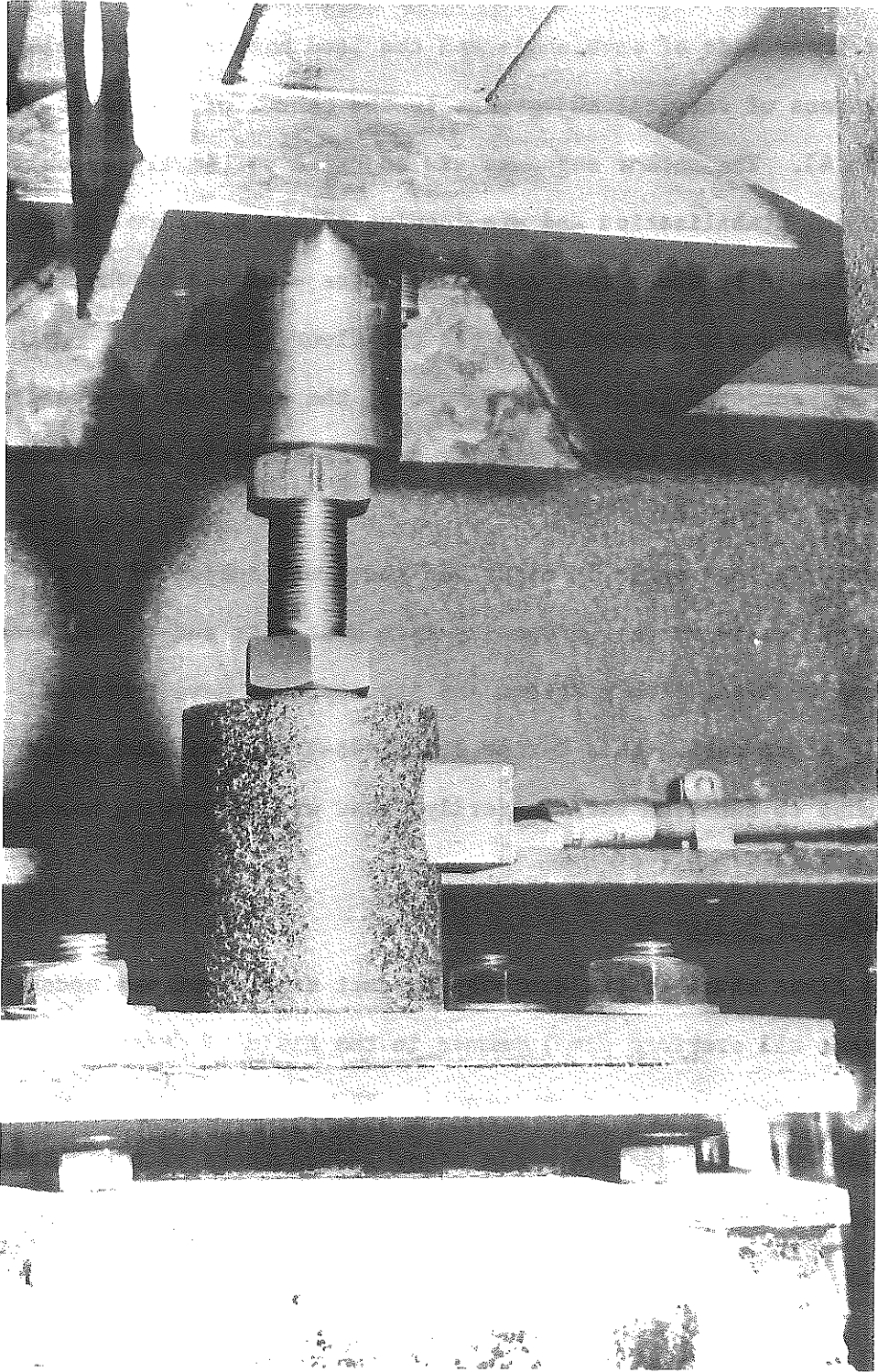


Figure 4. Leveling Device - Broken Bridge Scale.

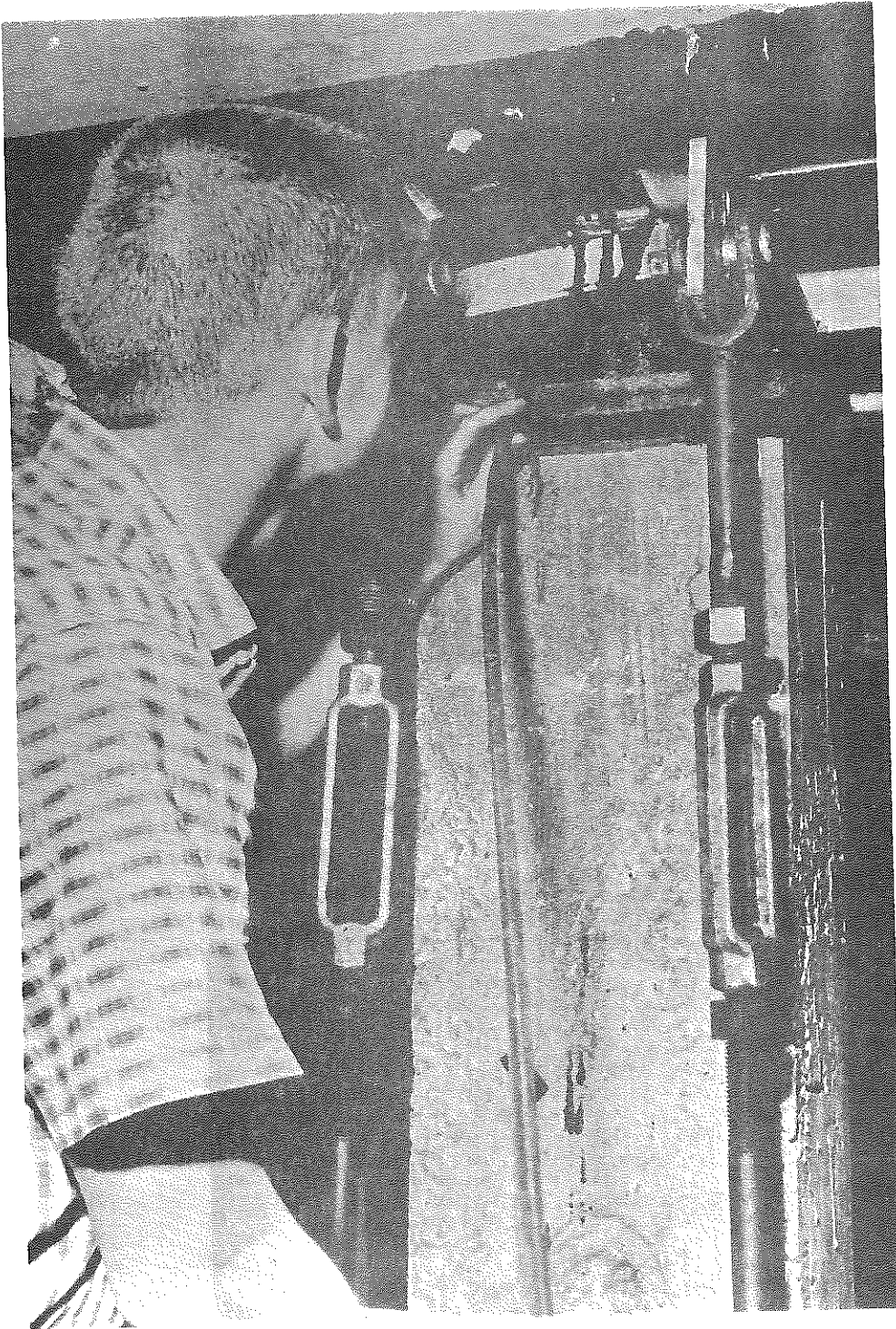


Figure 5. Rod and Turnbuckle Preload Device.



Figure 6. Coil Spring Preload Device.

a Type Cxx, 20,000# capacity Baldwin-Lima-Hamilton Load Cell. Adjustable, horizontal tie-bars or "flexures" at two diagonal corners serve to stabilize the platform in directions parallel and transverse to traffic. No provision was made in the original design for vertical stabilization or pre-loading. During the Kentucky research both the rod and turnbuckle arrangement and the heavy coil springs were added to the scale for these purposes.

The characteristic wave form output of the four load cell is nearly trapezoidal in shape with the top of the wave more likely to be sloping than horizontal (See Figure 2). The advantages and disadvantages of the longer sampling time afforded by the Taller-Cooper scale when compared to the discrete point sampling of the broken bridge are discussed in Chapter V.

The Beam-Type Scale

Utilization of the simple beam as a dynamic weight sensor was suggested by the strain measurement procedures used in a 1953 bridge vibration study (48). In 1956, a University of Kentucky graduate student applied strain gages to the beams supporting the platform of a lever type static scale and with this make-shift apparatus succeeded in measuring the dynamic wheel loads of passing trucks. The results of these early experiments indicated the practicality of proceeding with the design and testing of a prototype (Figure 7).

The first problems to be solved were the determination of the best cross sectional shape for the beams and the material from which they should be made. Static loadings of beams of different cross sections showed that a square or rectangular shape produced a load-strain relationship that was consistently linear - this was not the

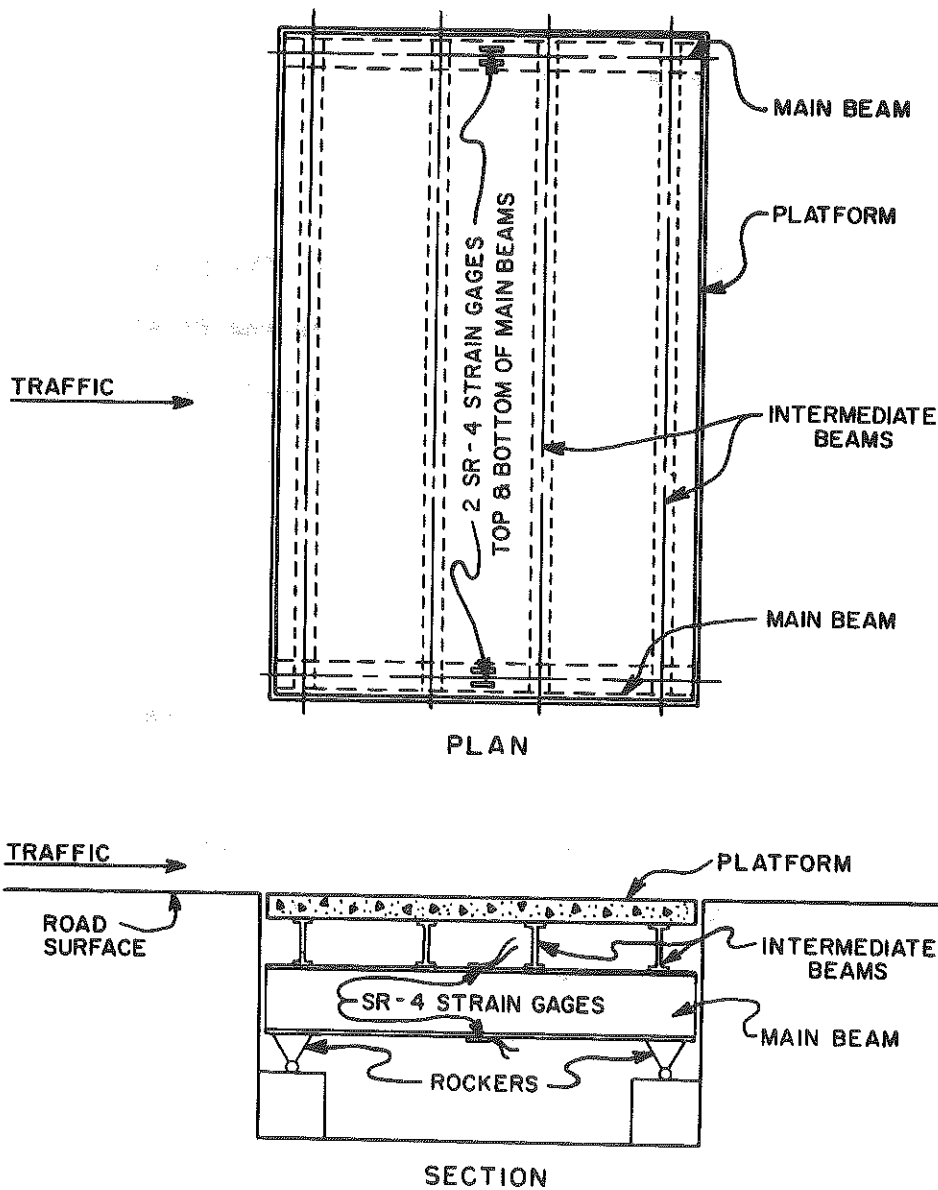


Figure 7. Schematic - The Beam Type Scale.

case for the other standard shapes tested. To obtain maximum output from instrumented beams a material was needed which would deflect a measurable amount under a wide range of applied loads. The material selected was a high strength aluminum alloy (7075-T6) with a recommended working stress of 33,000 psi and a modulus of elasticity (E) of 10,000,000 psi. A beam made of this alloy is as strong as a steel beam of comparable size but will deflect about three times as much under the same load.

The weight sensing beams that finally evolved were 4" x 6" in cross section and about 36" long. After being anodized the beams were sent to the David Taylor Model Basin of the U. S. Navy Department in Washington, D. C. Here, Navy technicians applied (and waterproofed) two different types of strain gages to the top and bottom of each beam near its mid-point. A detailed description of the gages and the waterproofing methods used is in Appendix B. With gages on the top and bottom of each beam it became possible, with appropriate wiring, to cause the tensile and compressive strains to add, thus doubling the output of the system. The wiring was also arranged to eliminate the weighing error due to the lateral displacement of a vehicle's wheel from the ideal location directly over the beams (see Appendix C).

An experimental platform was fabricated for the beam scale from two steel tee beams tied together with straps under the adjacent flanges and with the 7/8" thick x 7" high webs resting on the aluminum beams at positions about 7 1/2" on either side of the mid-points. This resulted in a platform that measures 2'-4" x 10'-0", the size needed to fit the existing pit in which the beam scale was to be installed for testing.

CHAPTER III

THE TESTING PROGRAM

The Test Sites

It was decided early in the Kentucky project that the testing program should be carried out at a location near one of the State's truck weighing stations. Such a location would provide a ready means of obtaining comparative static axle weights and would assure a constant supply of passing trucks from which a test sample could be diverted. After considering several locations on Federal Highways near Lexington, the decision was made to construct the test scale pits in the approach ramp to the North Loadometer Site on Interstate Highway 64 near Shelbyville, Kentucky. At that time (1961) the grade and drain had just been completed on the highway and construction of the Loadometer Site had not yet commenced. Since it was apparent that some time would elapse before testing could begin at the I-64 Site, a temporary installation of the broken bridge scale was made in a service road on the University of Kentucky Experimental Farm in Lexington.

The U. K. Farm Test Site provides scale approaches from the north and south of about 400 and 800 feet, respectively. The original crushed rock surface was stabilized initially with a bituminous surface treatment at the outer ends of the approaches. Due to excessive deterioration of the surface under traffic and weather it later became necessary to pave these sections with bituminous concrete. The immediate approaches to the scale pit (100 feet to the north and 25 feet to the south) were brought to a uniform 0.5% grade, leveled transversely and paved with six inches of portland cement concrete. Further modifications were made to the approaches as the testing proceeded (Figure 8 and 9).



Figure 8. The UK Farm Test Site - looking South.

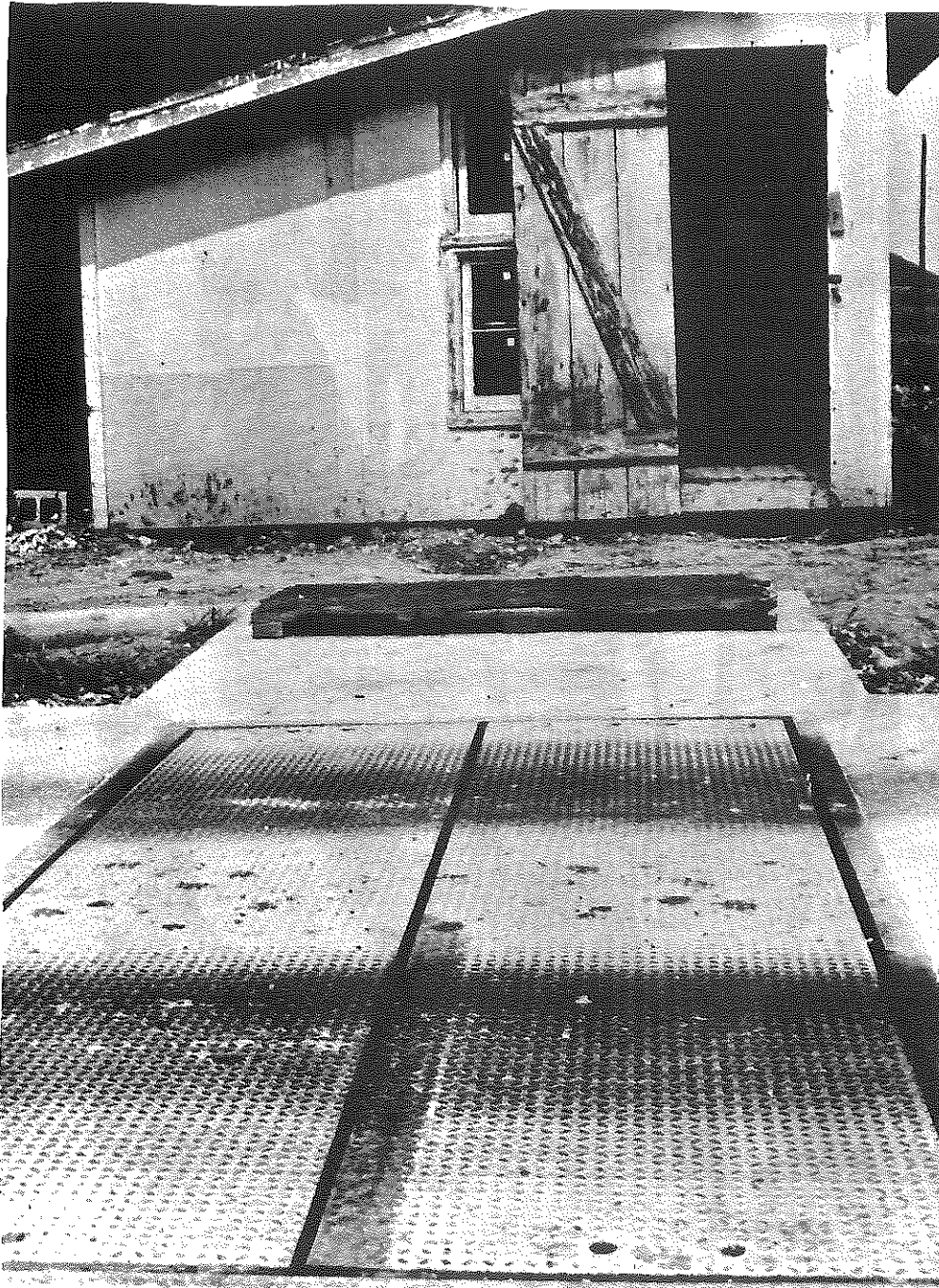


Figure 9. Broken Bridge Platform and Instrument Shed -- UK Farm Test Site.

The reinforced concrete pit for the Broken Bridge scale is equipped with electrical outlets, conduit connections to the instrument shed and an automatic sump pump. Sufficient headroom is provided in the pit for ease of movement when changing pre-load settings, leveling the platform, etc.

Construction of the scale pits and approaches at the I-64 Test Site was started in late July, 1962 and was completed in mid-November of that year. The pits for Teller-Cooper and the Broken Bridge Scales, are located fifty feet apart in the right lane of the approach ramp to the North Loadometer Site at a point about 650 feet east of the static scale house (Figure 10). The pavement slab in which the pits are situated was designed specifically for the project and was poured monolithically with the pit walls. This section of the pavement is level longitudinally but is sloped transversely at a rate of three-sixteenths of an inch per foot. All reasonable precautions were taken to assure a smooth but not slick pavement surface on the approach to the scale pit.

Each scale pit is well lighted and is provided with a sump pump and the necessary terminal boxes, conduits, outlets, etc (Figure 11). To remove the distracting effect (to the truck drivers) of an instrument shed near the scale platforms, it was decided to install the recording devices in the static scale house. This introduced some additional problems due to the long cable length required between the pits and the scale house. Portions of the cable adjacent to the pits and the scale house were placed in underground conduits; the remainder was supported above ground on a fence that parallels the approach ramp (See Appendix C).

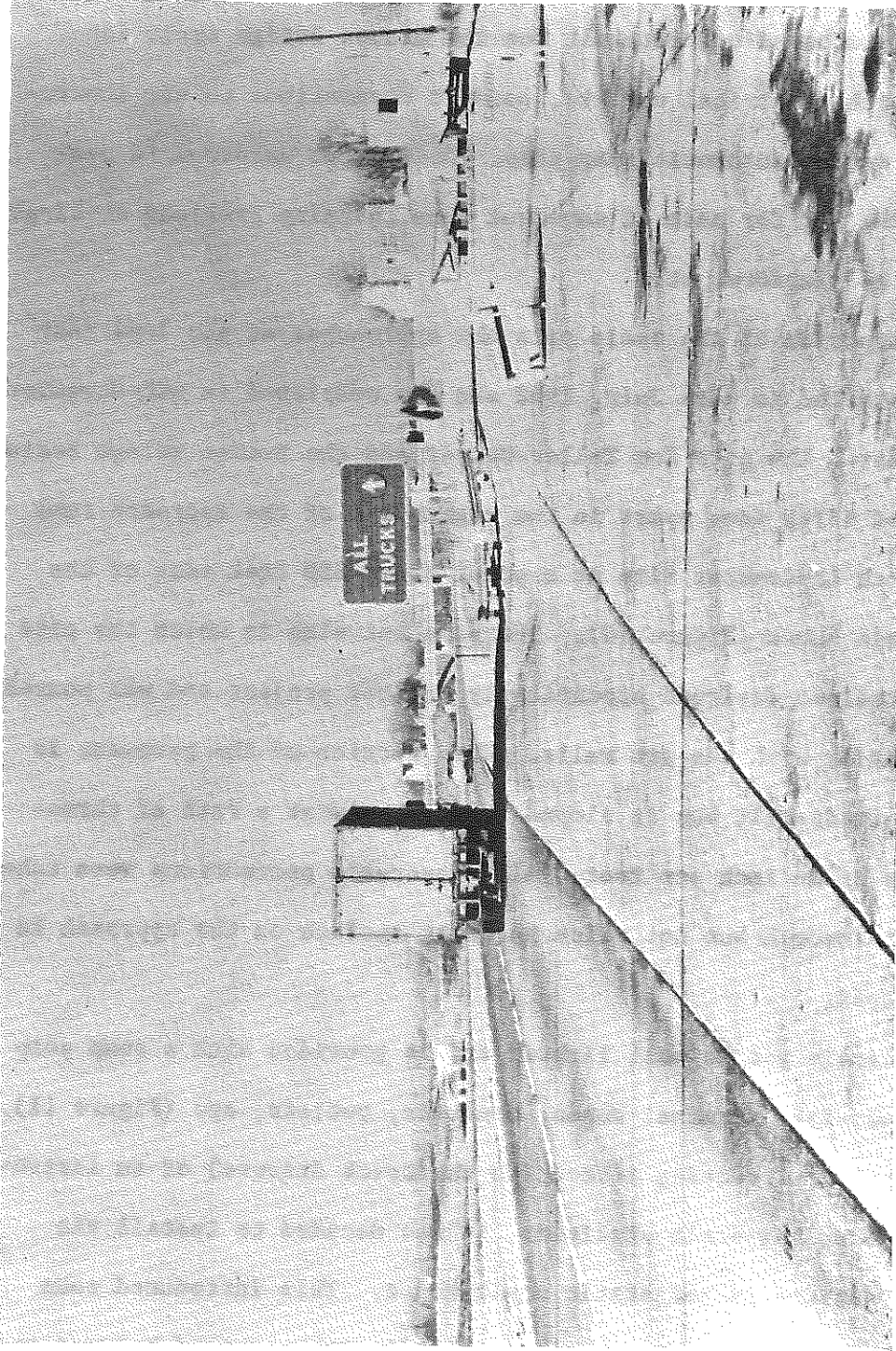


Figure 10. The Interstate Highway 64 Test Site.

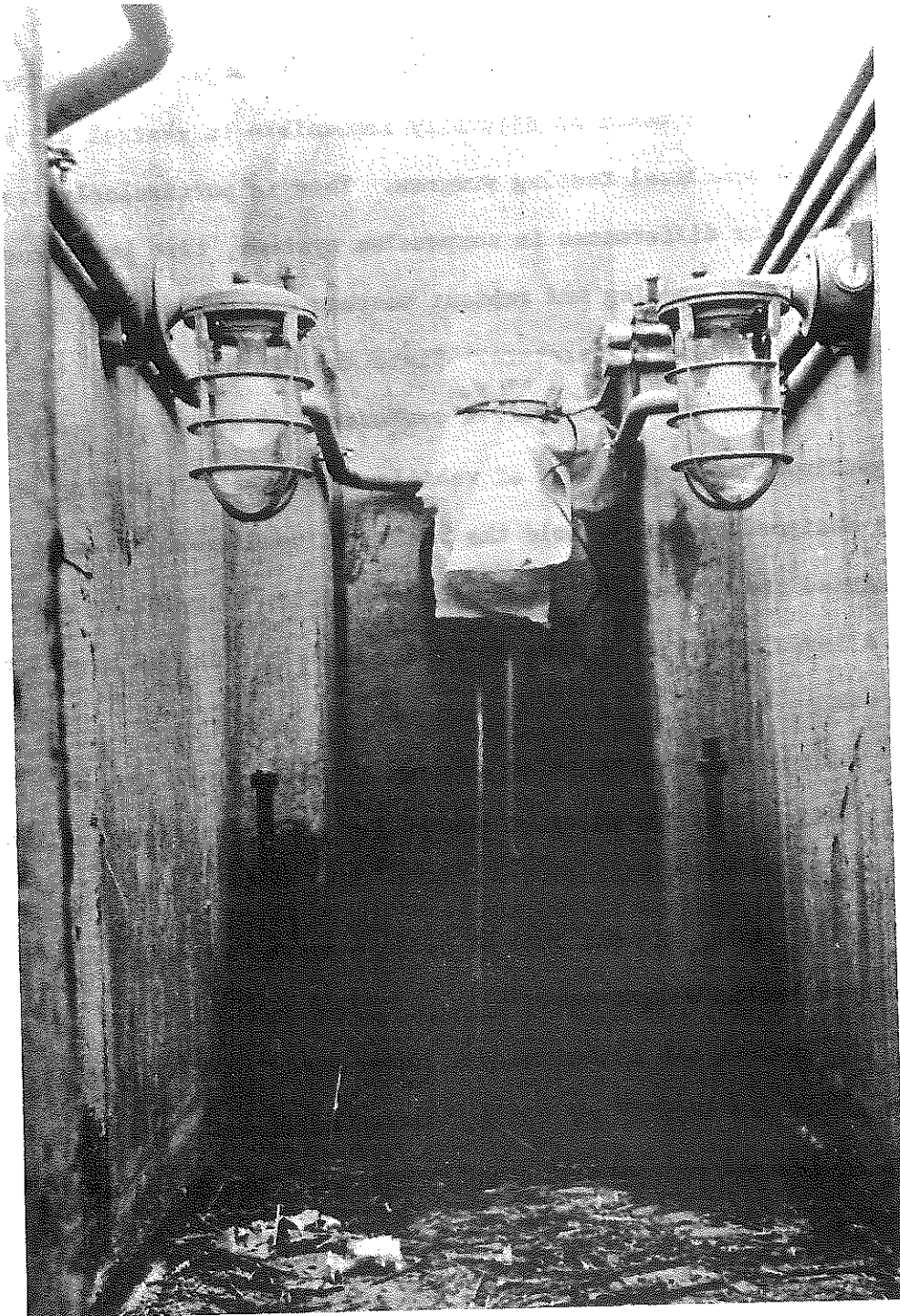


Figure 11. Interior of Scale Pit - I 64 Test Site (Taller Cooper Scale Pit).

The Test Variables

So many variables influence the dynamic weight of a moving vehicle that it would be virtually impossible to control all of them in a practical testing program. This is particularly true of vehicular differences in suspension systems, tire pressures, cargoes, axle spacing and ambient weather conditions such as wind velocity and temperature. Since the primary goal of the Kentucky project was a comparative evaluation of different scale configurations and not a study of vehicle dynamics, the testing procedure was designed to either hold the vehicular conditions constant or to minimize the overall effect of the variations by weighing the axles of a large number of trucks diverted directly from the normal traffic stream.

The testing program which evolved from the above considerations was divided into two distinct phases for each scale type and preload condition:

(1) a number of test runs at various speeds using a test vehicle of known static weight and,

(2) dynamic and static weight measurements of 200 or more axles from a "random sample" of trucks diverted from the traffic stream with no control of approach speed other than that exercised by the individual driver.

Testing at the U.K. Park Site was limited to the first phase and was, of course, concerned only with the Broken Bridge scale. Variables introduced into the program at this site included:

(1) Test truck types: a two axle dump and a three axle truck-mounted air compressor.

(2) Approach speeds: 10 mph to 30 mph

(3) Amount of vertical pre-load: 0%, 100% and 200% of the static weight of the front axle of the test vehicle or about 0, 5000 and 10,000 pounds, respectively

(4) Method of applying preload: stiff rods with turnbuckles and heavy coil springs.

(5) Approach conditions: unmodified, smoothed with an epoxy-sand leveling course and paved with a continuous bituminous concrete covering over both the approaches and the platform (Figures 12 and 13).

(6) Direction of approach: northbound and southbound.

Theoretical inquiries into the nature and effect of preloading and the vibrational characteristics of the Broken Bridge were made by members of the project staff during the Farm Site tests. Pertinent excerpts from the published and unpublished results of these investigations (76, 20) are in Appendix D.

The materials and procedures used in applying the epoxy-sand leveling course to the southbound approach are discussed in Appendix E.

All three scale types were tested at the I-64 Site. It was possible there to apply both phases of the testing program. Variables included in the tests were:

(1) Truck types: a loaded two axle truck for the phase one tests and a random selection of two to five axle trucks for the phase two tests.

(2) Approach speeds: 10 to 50 mph, incremented in 5 mph steps, for phase one and varying from 10 to 40 mph for the random samples.

(3) Amount of vertical preload: 0, 6000 and 12,000 pounds, representing respectively 0%, 50% and 100% of the static weight of the rear axle of the test vehicle.

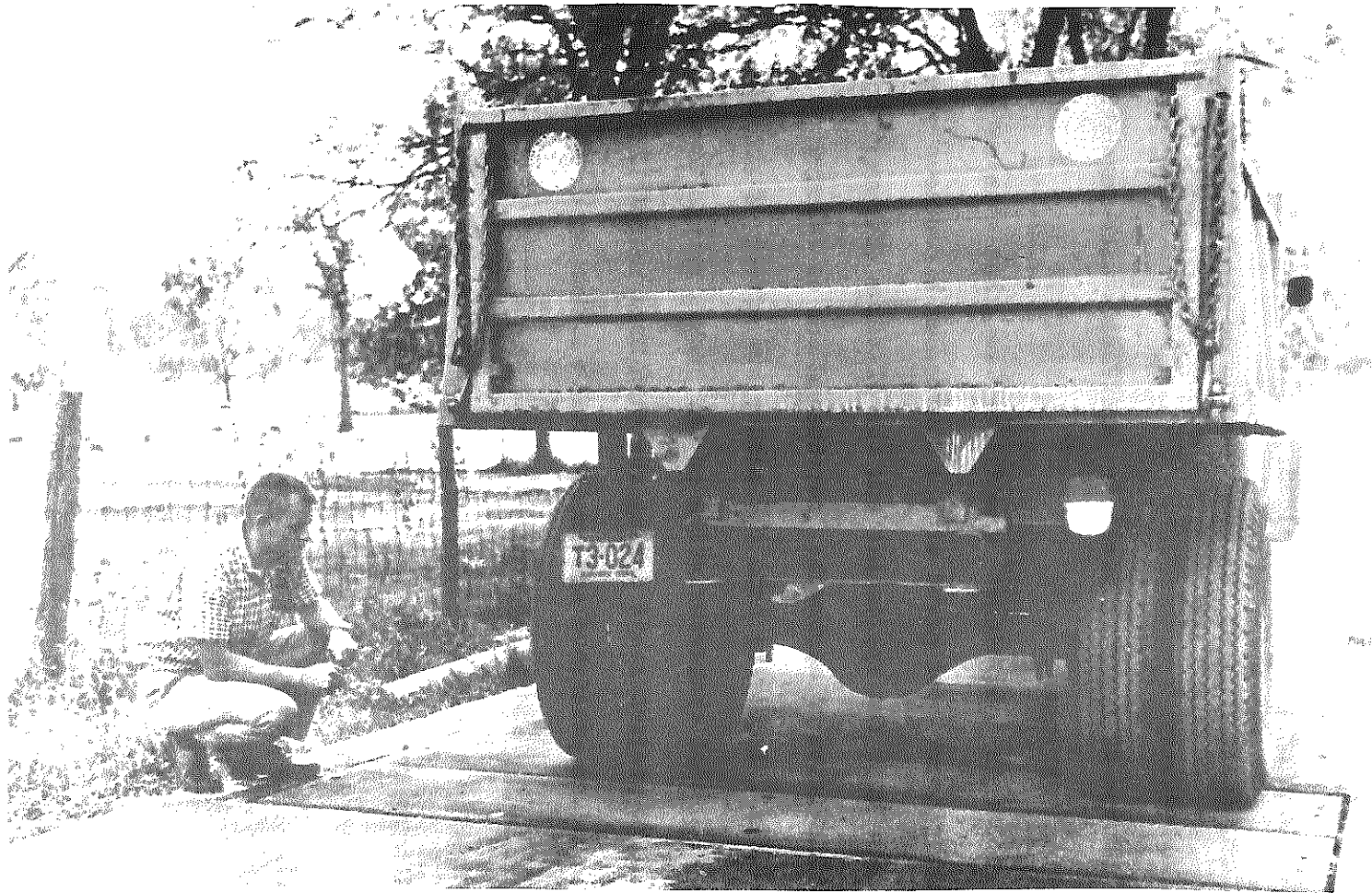


Figure 12. Approach Slab and Scale Platform after Application of Epoxy-sand Leveling Course - UK Farm Test Site.



Figure 13. Approach Slab and Scale Platform after Application of Bituminous Concrete Overlay - UK Farm Test Site.

(4) Method of preloading: Stiff rods with turnbuckles and coil springs for the Teller-Creper scale and springs only for the Broken Bridge; the beam type scale was not preloaded.

The approach conditions were not changed during the tests. However, dummy scale platforms were painted on the pavement between the two scale pits in an attempt to prevent deliberate braking or accelerating while crossing the actual platform. The westbound approach was used for all test runs.

Chapter IV
Analysis of Results

Data Reduction

All of the dynamic weight data collected during the various phases of the testing program were obtained from deflections traced on paper tape by the recorder stylus. Since the tape was graduated in millimeters, it was necessary to calibrate the scale recordings so that the deflections could be converted to weight. These conversion factors ranged from 500 to 800 pounds per millimeter. The maximum error of any individual reading was approximately 0.5 millimeters. Under these conditions, the maximum error due to reading the tape would be between $\pm 5\%$ and $\pm 8\%$ for a relatively light 5000 pound axle. For weights greater than 5000 pounds, the percent of error would, of course, be correspondingly lower.

The wave form generated by each of the scales under dynamic loading was also a significant factor in the data reduction procedure. The typical output wave form of the Tallor-Cooper scale is, as previously described, trapezoidal in shape with a sloping top, while that of the beam scale is a two-peaked affair with one peak usually higher than the other. For both of these scales, the dynamic weight was determined by averaging the millimeter readings of the high and low points (or peaks) of the wave form. The single peaked indication of the Broken Bridge scale presented no tape reading difficulties.

By considering the above sources of accidental error it was determined that a minimum of five runs of the test vehicle would be required for each combination of variables in the phase one test series. It was also evident

that a portion of the difference between the static and dynamic weight of a given axle amounting to about 5 to 8 percent of the static weight could theoretically be attributed to these random errors. Due to the plus and minus nature of random errors, the accumulation of actual error from tape reading would be dependent upon the sample size.

The deflections in millimeters as read from the tape and the conversion or scaling factor formed the input for a data reduction program written for the IEM 1620 computer. The computer output for the phase one runs included: the average, maximum and minimum deviations of the reading from the mean of five or more runs across the scale at "creep speed" (about three miles per hour), the mean and standard deviation of the readings for each axle and the root mean square error of the deviations from the creep speed mean. A similar program was used to expedite the reduction of data collected during the phase two or "random sample" runs. In phase two, the static weight of each axle of each truck diverted from the I-64 traffic was measured at the static scale house. These static weights were included in the input data for the computer. Output included (for both scales): the static and dynamic weight of each axle, the difference between static and dynamic weight in pounds and percent, the axle spacing and the approximate speed. The latter two items were obtained from the known speed of movement of the tape through the recorder, the known distance (50 feet) between the two scale pits and the relative locations on the tape of the dynamic weight indications for each axle. Typical output of the data reduction programs is shown in Figures 14 and 15.

Results of Tests at the U. K. Farm Site

Initial testing of the Broken Bridge scale was concerned with evaluating its performance under varying conditions of vehicle speed, preloading and approach surface smoothness. Figure 16 is typical presentation of

WEIGHTING VEHICLES IN MOTION

DYNAMIC WEIGHT DATA FOR TALLER^o COOPER AND BROKEN BRIDGE PLATFORMS

COMPARISON OF PRELOAD AT VARIOUS MPH

PRELOAD 50.0 PERCENT

TALLER^o COOPER PRELOAD^o STIFF TURNBUCKLESBROKEN BRIDGE PRELOAD^o SPRINGS

PRELOAD IN PERCENT OF REAR 1 AXLE

TALLER^o COOPER PLATFORM

AXLES

	FRONT	REAR 1	REAR 2	REAR 3	REAR 4	REAR 5	REAR 6	REAR 7
CREEP AVERAGE	4.8	14.4	0.0	0.0	0.0	0.0	0.0	0.0
AVERAGE DEFLECTION	5.0	15.2	0.0	0.0	0.0	0.0	0.0	0.0
FOLLOWING DEVIATIONS COMPARED WITH CREEP AVERAGE								
MAXIMUM DEVIATION FROM CREEP AVERAGE (PERCENT)	3.0	10.7	0.0	0.0	0.0	0.0	0.0	0.0
MINIMUM DEVIATION FROM CREEP AVERAGE (PERCENT)	3.0	3.8	0.0	0.0	0.0	0.0	0.0	0.0
DEVIATIONS OF AVERAGE FROM CREEP AVERAGE (PERCENT)	3.0	5.5	0.0	0.0	0.0	0.0	0.0	0.0

FR^oR1 R1^oR2 R2^oR3 R3^oR4 R4^oR5 R5^oR6 R6^oR7

AXLE SPACING	14.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0
--------------	------	-----	-----	-----	-----	-----	-----	-----

BROKEN BRIDGE PLATFORM

AXLES

	FRONT	REAR 1	REAR 2	REAR 3	REAR 4	REAR 5	REAR 6	REAR 7
CREEP AVERAGE	7.8	21.3	0.0	0.0	0.0	0.0	0.0	0.0
AVERAGE DEFLECTION	7.3	21.6	0.0	0.0	0.0	0.0	0.0	0.0
FOLLOWING DEVIATIONS COMPARED WITH CREEP AVERAGE								
MAXIMUM DEVIATION FROM CREEP AVERAGE (PERCENT)	1.9	3.0	0.0	0.0	0.0	0.0	0.0	0.0
MINIMUM DEVIATION FROM CREEP AVERAGE (PERCENT)	-10.8	-1.6	0.0	0.0	0.0	0.0	0.0	0.0
DEVIATIONS OF AVERAGE FROM CREEP AVERAGE (PERCENT)	-6.3	1.1	0.0	0.0	0.0	0.0	0.0	0.0

FR^oR1 R1^oR2 R2^oR3 R3^oR4 R4^oR5 R5^oR6 R6^oR7

AXLE SPACING	14.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0
--------------	------	-----	-----	-----	-----	-----	-----	-----

SPEED DETERMINATION

SPEED RUNS 1 TO 5 12.1 11.9 11.5 11.8 12.1 MPH

SPEED RUNS 6 TO 10 12.3 12.3 11.9 12.1 11.7 MPH

AVERAGE SPEED 12.0 MPH

TALLER^o COOPER PLATFORM

AXLES

FRONT REAR 1 REAR 2 REAR 3 REAR 4 REAR 5 REAR 6 REAR 7

Figure 14. Typical Output of Data Reduction Program
Test Truck (Phase One) Runs

WEIGHING VEHICLES IN MOTION

RANDOM SAMPLES

PRELOAD 100.0 PERCENT

TC SCALING FACTOR, 834.0 LB/MM									
BB SCALING FACTOR, 527.0 LB/MM									
SAMPLE NUMBER 6131963 80									
STATIC WEIGHT	3740.	6860.	0.	0.	0.	0.	0.	0.	0.
DYNAMIC WGT TC	5004.	7089.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (LB)	1264.	229.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (PCT)	33.7	3.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AXLE SPCNG TC	14.9	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
STATIC WEIGHT	3740.	6860.	0.	0.	0.	0.	0.	0.	0.
DYNAMIC WGT BB	4743.	7905.	0.	0.	0.	0.	0.	0.	0.
DIFF BB (LB)	1003.	1045.	0.	0.	0.	0.	0.	0.	0.
DIFF BB (PCT)	26.8	15.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AXLE SPCNG BB	15.3	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SPEED	29.9 MPH								

SAMPLE NUMBER 6131963 91									
STATIC WEIGHT	6240.	6880.	0.	0.	0.	0.	0.	0.	0.
DYNAMIC WGT TC	7089.	7506.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (LB)	849.	626.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (PCT)	13.6	9.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AXLE SPCNG TC	15.7	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
STATIC WEIGHT	6240.	6880.	0.	0.	0.	0.	0.	0.	0.
DYNAMIC WGT BB	7114.	7378.	0.	0.	0.	0.	0.	0.	0.
DIFF BB (LB)	874.	498.	0.	0.	0.	0.	0.	0.	0.
DIFF BB (PCT)	14.0	7.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AXLE SPCNG BB	13.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SPEED	20.7 MPH								

SAMPLE NUMBER 6131963 97									
STATIC WEIGHT	4320.	6440.	0.	0.	0.	0.	0.	0.	0.
DYNAMIC WGT TC	4587.	6672.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (LB)	267.	232.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (PCT)	6.1	3.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AXLE SPCNG TC	13.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
STATIC WEIGHT	4320.	6440.	0.	0.	0.	0.	0.	0.	0.
DYNAMIC WGT BB	4743.	6587.	0.	0.	0.	0.	0.	0.	0.
DIFF BB (LB)	423.	147.	0.	0.	0.	0.	0.	0.	0.
DIFF BB (PCT)	9.7	2.2	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AXLE SPCNG BB	15.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
SPEED	18.8 MPH								

SAMPLE NUMBER 6131963 104									
STATIC WEIGHT	4020.	5680.	0.	0.	0.	0.	0.	0.	0.
DYNAMIC WGT TC	4587.	6255.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (LB)	567.	575.	0.	0.	0.	0.	0.	0.	0.
DIFF TC (PCT)	14.1	10.1	0.0	0.0	0.0	0.0	0.0	0.0	0.0
AXLE SPCNG TC	13.8	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Figure 15. Typical Output of Data Reduction Program
Random Sample (Phase Two) Runs

the phase one test results. It shows for each axle the percent deviation at various speed levels of the mean of five or more test runs from the mean weight at creep speed (equivalent to static weight). Separate graphs are shown for each approach direction. The results obtained after application of the epoxy-sand leveling course are indicated by the encircled axle numbers. The curves of Figure 16 indicate that for the zero preload condition, the smoothing of the approach surface tended to reduce the deviations at the 30 mph crossing speed although large deviations still occurred at 20 mph. Figure 17 shows that the application of a 10 kip preload by a rod and turnbuckle device reduced the deviations slightly for the two axle test vehicle. Other runs were made using the two axle truck with a 5 kip preload on the scale. No significant difference from the results of the 10 kip preload condition was noted.

The effect of preload was much more apparent when the three axle test vehicle was used. Figure 18 shows the deviations under the zero preload condition for the southbound approach only. Modification of approach surface smoothness is indicated by separate sets of curves for the three axles. The extremely high deviation for the second axle of the tandem may be the result of residual vibrations in the weighing system due to the passage of the first tandem axle (16). The addition of a 10 kip preload to the platform reduced the deviations to a maximum of $\pm 15\%$ for all axles at an approach speed of 30 mph over the smoothed surface. For the unmodified approach surface, maximum deviations of up to 20 percent occurred again at 20 mph.

In anticipation of the possibility that the Broken Bridge scale might be used to continuously record the dynamic axle weights of vehicles in the normal traffic stream, it was decided that the scale should be tested with the platform and the immediate approaches paved with 2 inches of bituminous

concrete. Such a cover or overlay would not only provide protection for the scale mechanism and a smooth crossing surface but would also effectively camouflage the entire installation.

A large number of test runs were made over the paved scale using the three axle truck mounted air compressor. An extensive investigation of the relative merits of the steel rod and turnbuckle versus the coil spring as a preload device was conducted during this test series. The results, which favored the latter method, are described in detail in Appendix D.

It was suspected that the weight and stiffness of the bituminous concrete overlay would tend to dampen the vibrational characteristics of the Broken Bridge and that the damping effect would vary with ambient temperature. Figures 20, 21 and 22 show the deviations from static weight for each axle under varying conditions of speed, preload, direction of approach and temperature. These curves show a remarkable consistency of shape and indicate quite clearly the difference in roughness between the northbound and southbound approaches. At the higher temperature level (95°F) nearly all deviations were depressed in a negative direction. This was particularly true for the rough southbound approach. An increase in preload reduced the deviations to a larger degree than when the same increase was applied to the unpaved scale. Maximum deviations of less than \pm 11 percent were attained for all speeds and temperatures under a preload of 10 kips when the test vehicle was traveling north. For southbound runs, the deviations ranged from 17 to 25%, the maximum values again occurring at 20 mph.

As a result of the above described tests, it was decided to use coil spring preload for all future work with the Broken Bridge scale. The I-64 site did not lend itself to further testing of the paved scale but it was concluded that the idea was both feasible and practical.

FIGURE 16.
 BROKEN BRIDGE SCALE
 TWO AXLE TEST TRUCK
 U.K. FARM TEST SITE
 PRELOAD-NONE

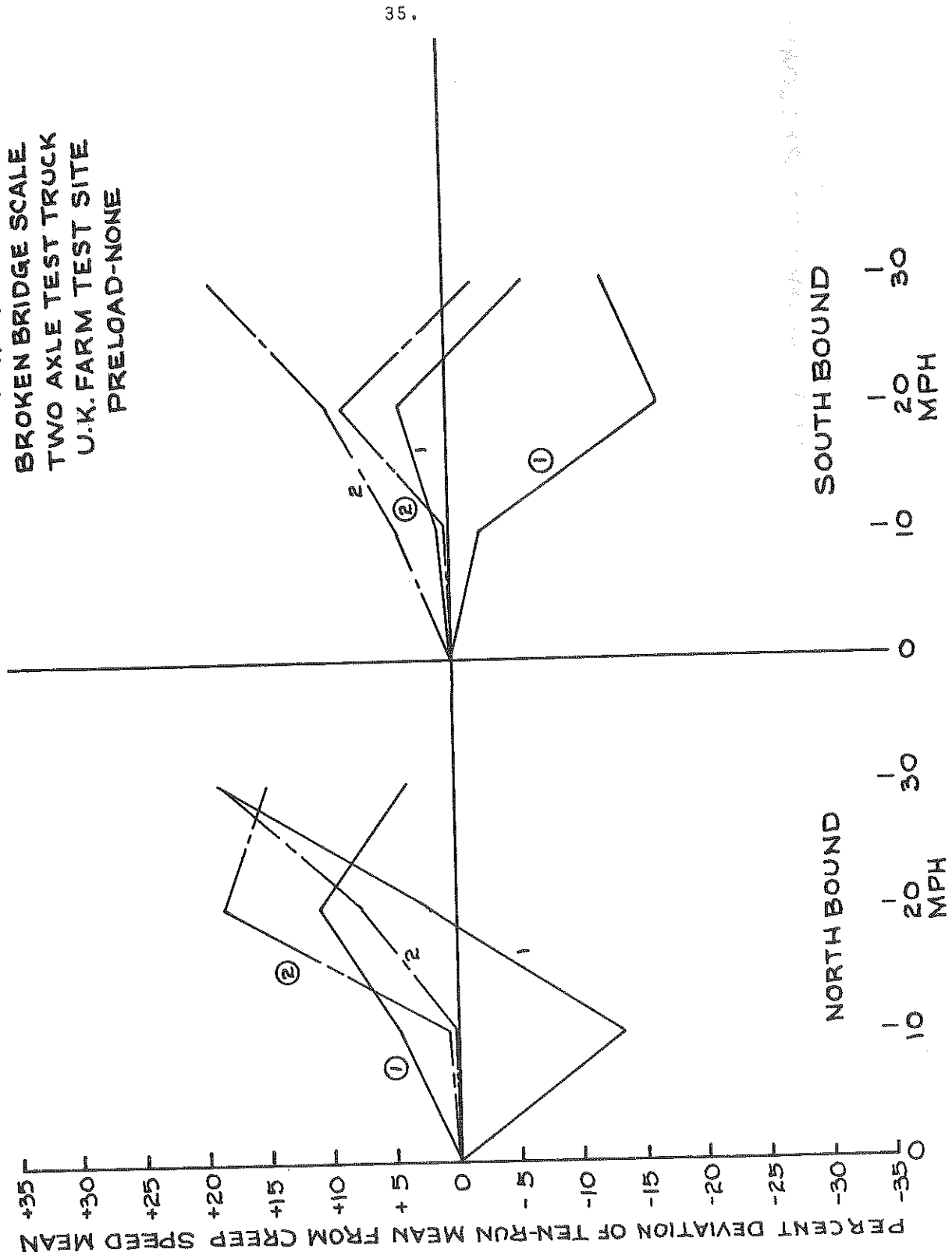


FIGURE 17.
 BROKEN BRIDGE SCALE
 TWO AXLE TEST TRUCK
 U.K. FARM TEST SITE
 PRELOAD-10 KIPS
 ROD & TURNBUCKLE PRELOAD

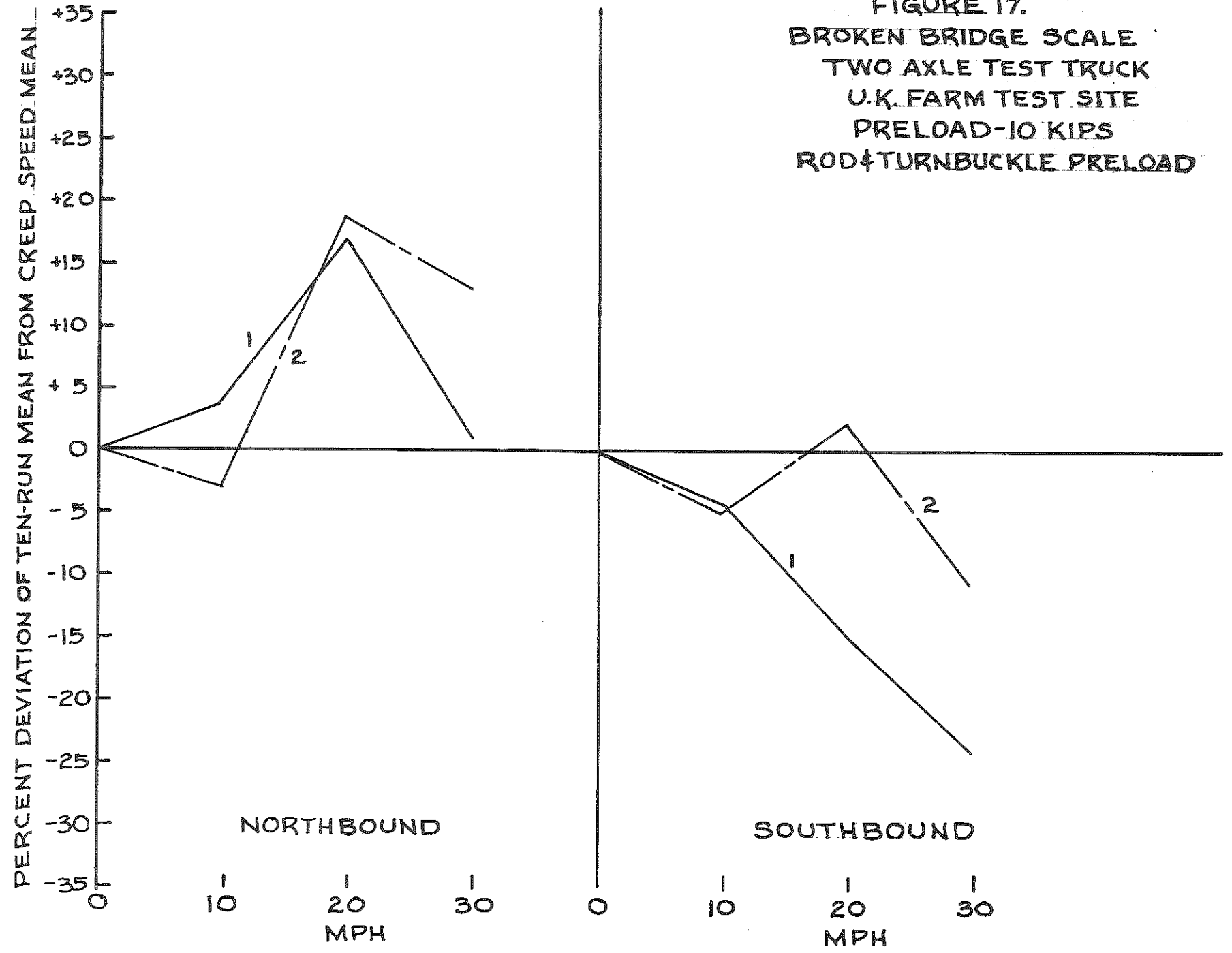


FIGURE 18.
 BROKEN BRIDGE SCALE
 THREE AXLE TEST TRUCK
 U.K. FARM TEST SITE - SOUTHBOUND
 PRELOAD-NONE

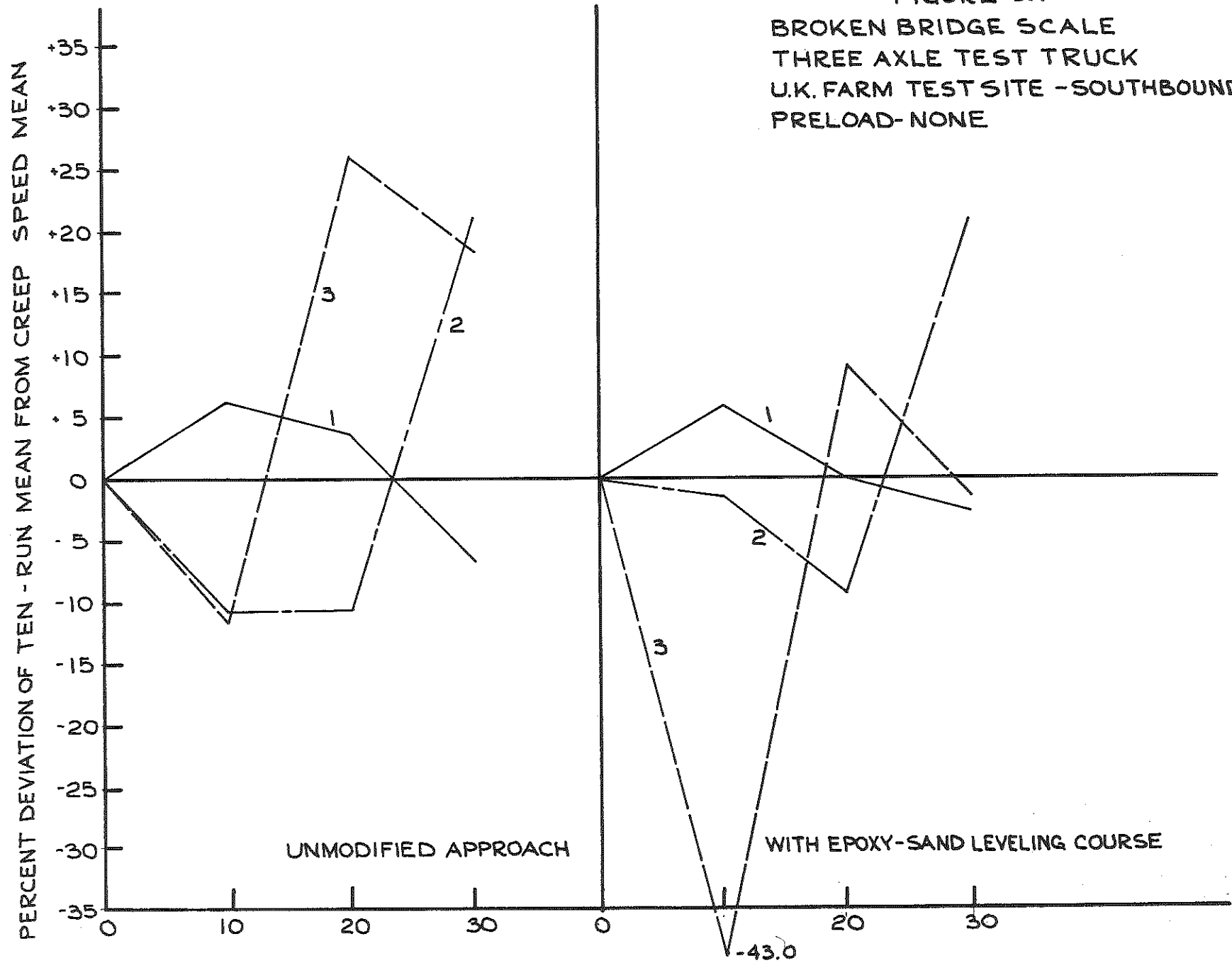


FIGURE 19.
 BROKEN BRIDGE SCALE
 THREE AXLE TEST TRUCK
 U.K. FARM TEST SITE - SOUTHBOUND
 PRELOAD - 10 KIPS
 ROD & TURNBUCKLE PRELOAD

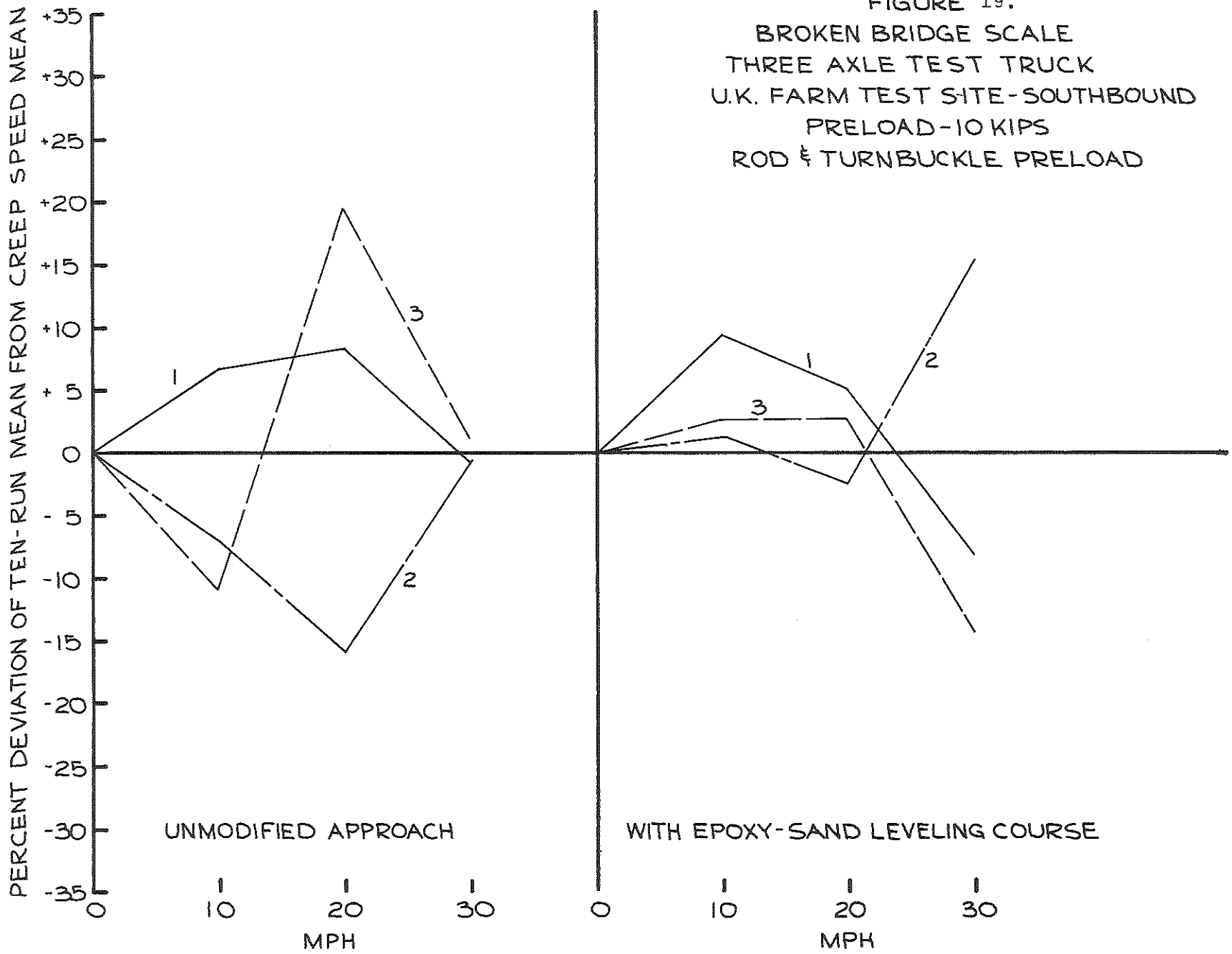


FIGURE 20.

BROKEN BRIDGE SCALE WITH BIT. CONC. COVER
U.K. FARM TEST SITE
THREE AXLE TEST TRUCK
PRELOAD-NONE
AXLE NO.- 0 - 70°F.
AXLE NO.- 1 - 95°F.

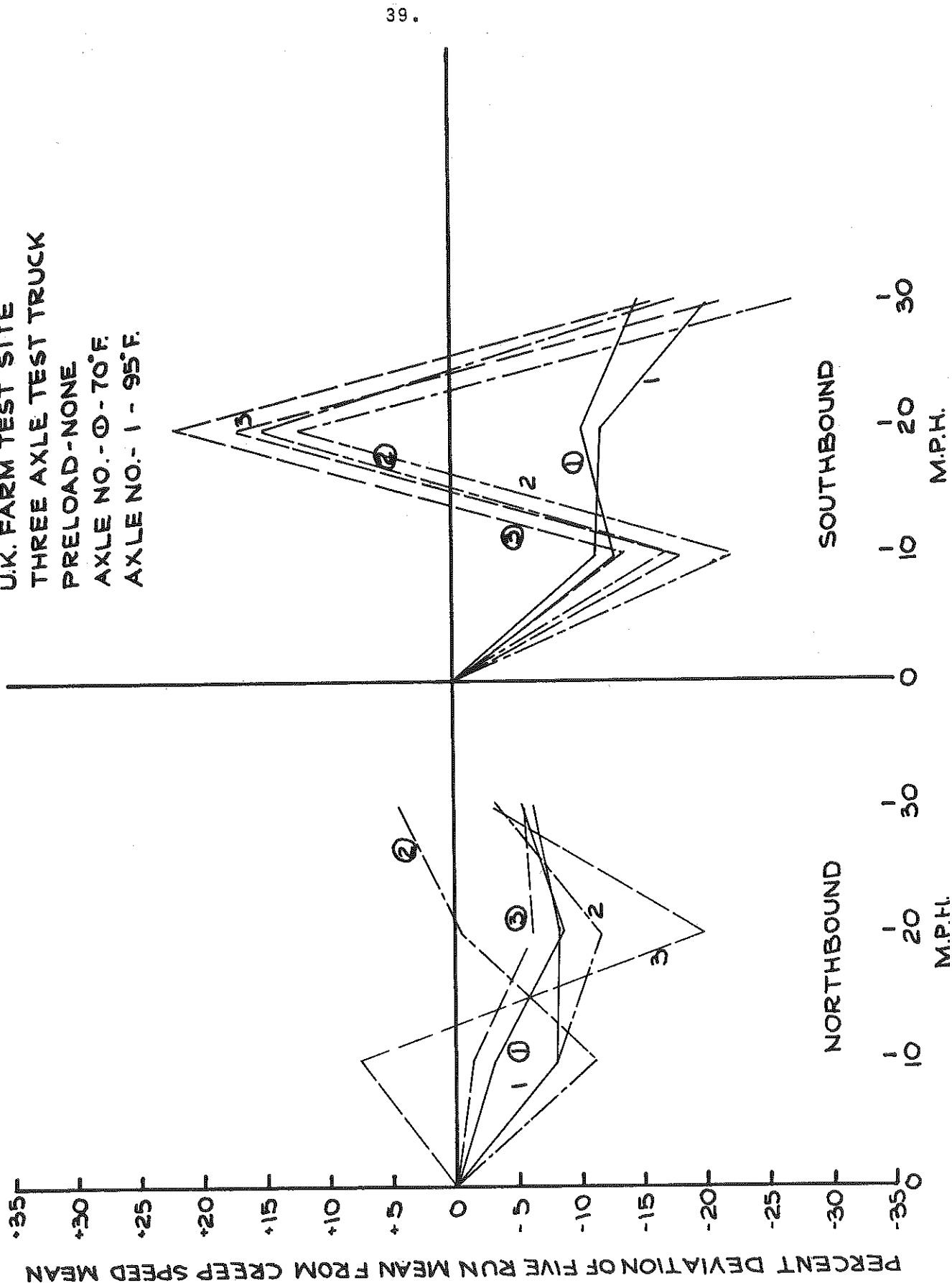


FIGURE 21.

BROKEN BRIDGE SCALE WITH BIT. CONC. COVER
U.K. FARM TEST SITE
THREE AXLE TEST TRUCK
PRELOAD - 5 KIPS
COIL SPRING PRELOAD

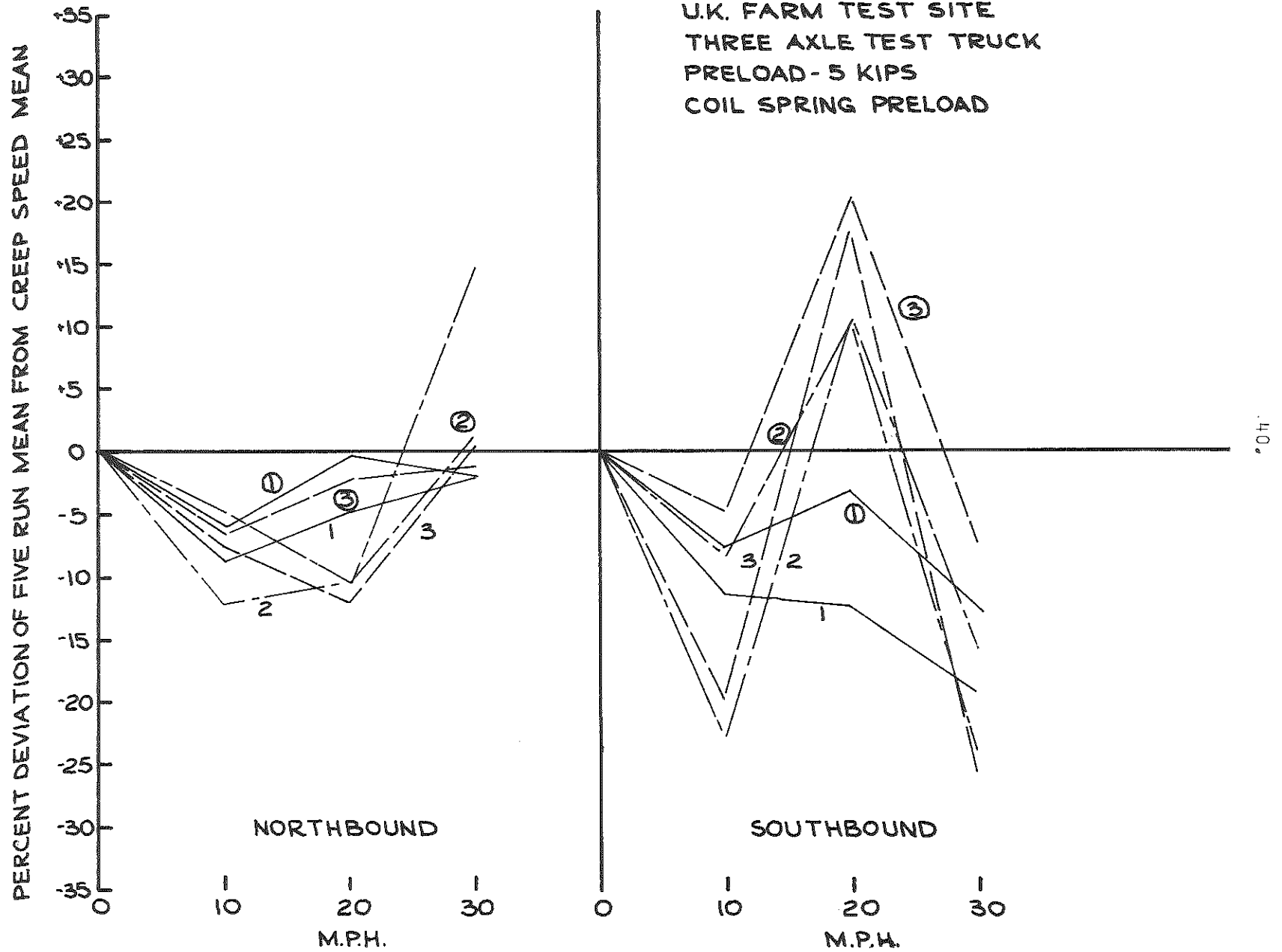
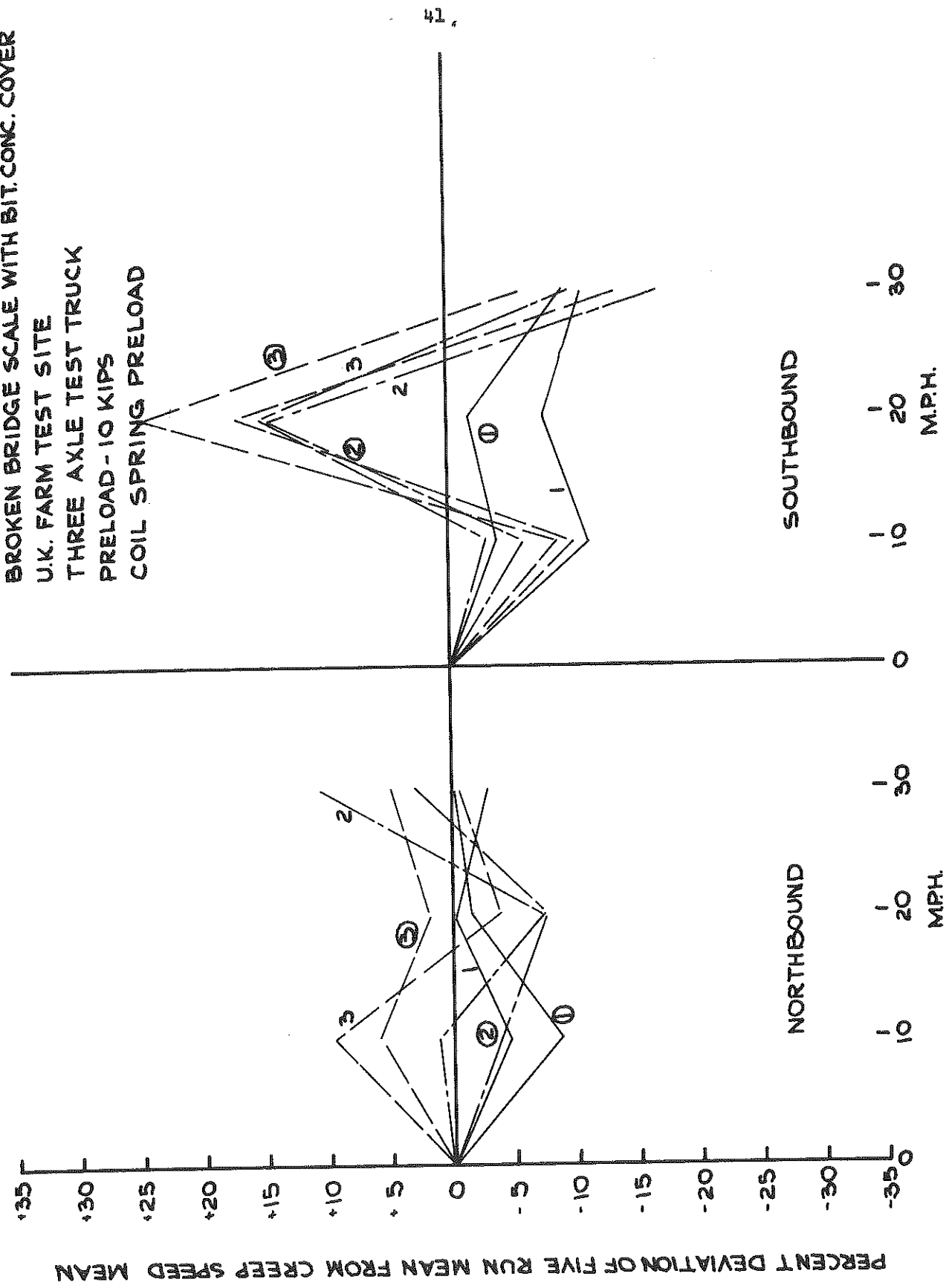


FIGURE 22.
 BROKEN BRIDGE SCALE WITH BIT. CONC. COVER
 U.K. FARM TEST SITE
 THREE AXLE TEST TRUCK
 PRELOAD - 10 KIPS
 COIL SPRING PRELOAD



Results of Phase One Tests at the I-64 Site.

Construction of a turnaround at the east end of the approach ramp to the I-64 site made it possible to study the effects of crossing speeds up to 30 mph. Maximum, average and minimum deviations for each axle of the test vehicle under various speed and preload conditions are shown in Figures 23 through 39. Results obtained from the Tallar-Cooper and Broken Bridge scales for the same axle and preload are arranged in pairs (Figures 23 through 37) for ease of comparison.

For the light (4060 lbs.) front axle of the test vehicle, the curves of Figures 23 through 28 show that an increase in preload tended to reduce the maximum range of the deviations at all speeds less than 35 mph. At speeds greater than 35 mph, the range of the deviations remained nearly the same regardless of the amount of preload applied. The average percent deviation for the front axle as weighed on the Tallar-Cooper scale increased slightly with an increase in preload at crossing speeds of 35 mph or less. Deviations computed for the Broken Bridge scale under identical circumstances varied from about +3% at zero preload to -9% and -6% under a 6 kip and 12 kip preload respectively.

Dynamic weight measurements of the 11,600 lb. rear axle varied from the static weight in the same general way as the front axle but the range of the deviations was narrower. Average percent deviations for both scales were higher than those obtained for the front axle for all combinations of speed and preload. Deviation curves for the rear axle as weighed by the two scales are in Figures 29, 31, 32, 34, 35 and 37.

When the initial series of test runs were completed, the coil spring preload device was removed from the Broken Bridge scale and installed on the Tallar-Cooper. The revised system was tested by weighing only the rear

axle of the test truck. The results, as shown in Figures 30, 33 and 36, were not greatly different from those obtained when the scale was preloaded by red and turnbuckle.¹ There was, however, a decided improvement in the smoothness of the output wave form.

Late in 1963, the Tallier-Cooper scale was removed from its pit and the experimental beam type scale was installed. A number of test runs were made across the scale with a vehicle like that used in previous tests. Site conditions at the time the runs were made restricted the crossing speed to a maximum of 35 mph. Deviations from static weight at this speed level and below were generally smaller than those attained with the other two scales. Figures 38 and 39 show the beam scale deviation curves. It should be noted that the values shown were obtained by computing the dynamic weight from an average of the readings for the two peaks of the output wave form.

The following table summarizes the results of the test truck runs at the I-64 site:

Table 1.

Average Percent Deviation of Dynamic Weight from Static Weight
2 Axle Truck, 10-35 MPH

Preload	Tallier-Cooper (Red & Turnbuckle)		Tallier-Cooper ² (Coil Spring)	Broken Bridge (Coil Spring)		Beam Type Scale ³	
	Front	Rear	Rear	Front	Rear	Front	Rear
Zero	7.7	11.2	--	4.9	17.5	5.5	6.6
6 Kips	8.3	13.2	12.8	-9.2	12.3	--	--
12 Kips	8.5	13.7	15.0	-6.1	11.1	--	--

¹Figure 30 is included to illustrate the repeatability of the Tallier-Cooper scale. The rear axle weight of the test truck used in the coil spring preload runs was about 800 lbs. lighter than that used in the original tests.

²Static weight of rear axle of test vehicle was 10000 lbs.

³Static weight of front and rear axle of test vehicle was 6940 lbs. and 8700 lbs. respectively.

FIGURE 23.
 TALLER-COOPER SCALE
 TWO AXLE TEST TRUCK-FRONT AXLE
 I-64 TEST SITE
 PRELOAD-NONE

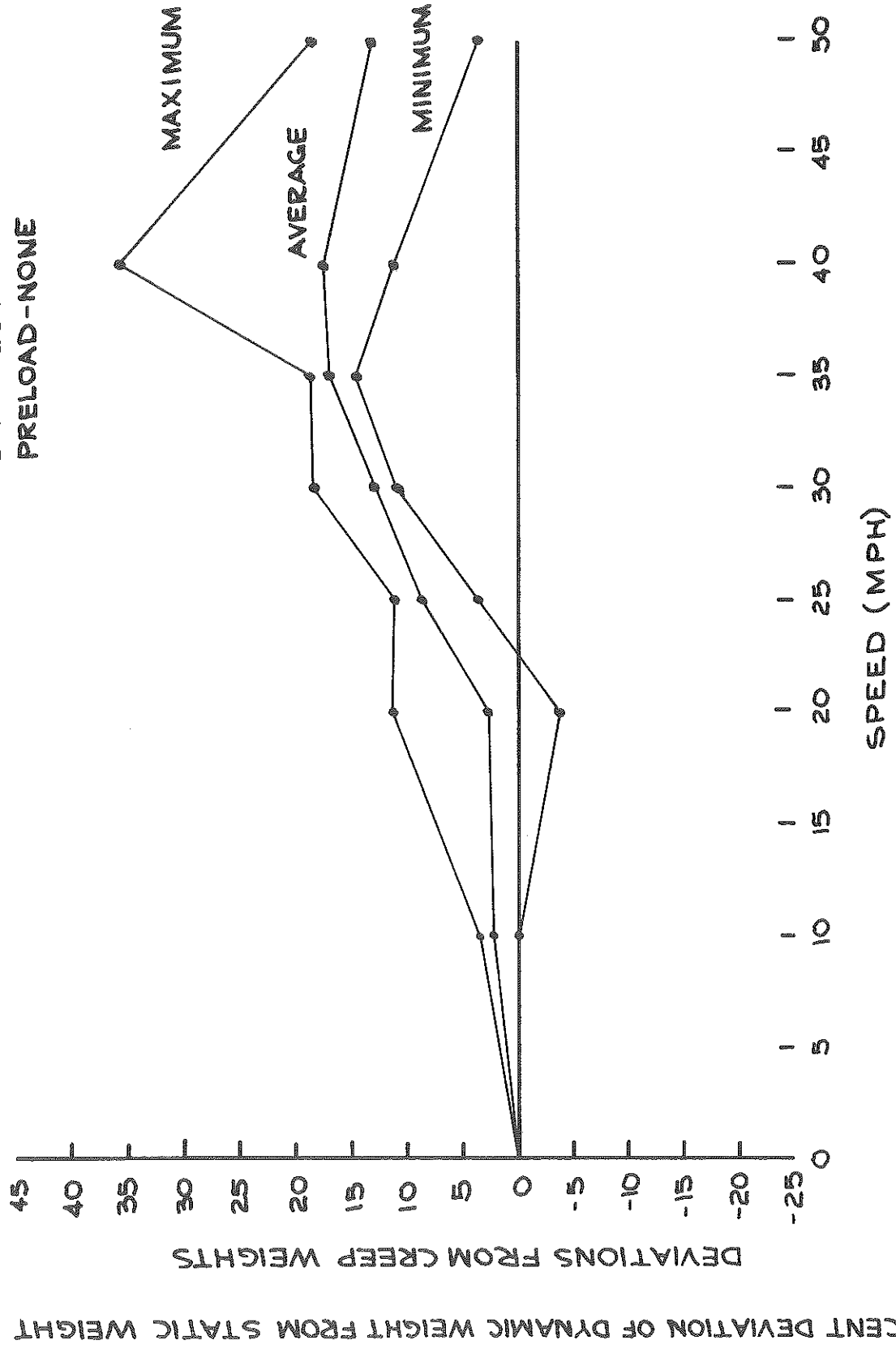


FIGURE 24.
BROKEN BRIDGE SCALE
TWO AXLE TEST TRUCK-FRONT AXLE
I-64 TEST SITE
PRELOAD-NONE
COIL SPRING PRELOAD

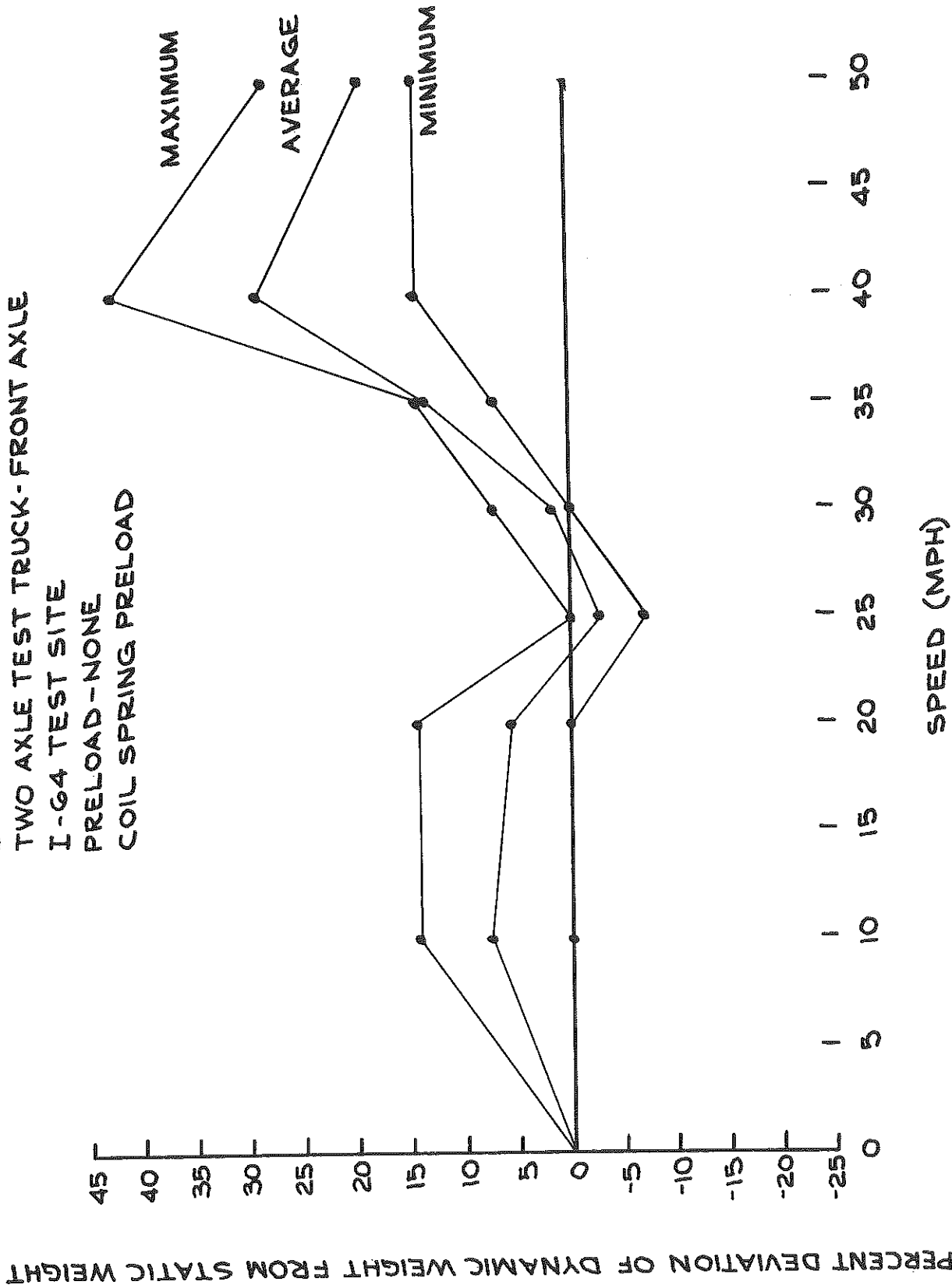


FIGURE 25.
 TALLER-COOPER SCALE
 TWO AXLE TEST TRUCK - FRONT AXLE
 I-G4 TEST SITE
 PRELOAD - 6 KIPS
 ROD & TURNBUCKLE PRELOAD

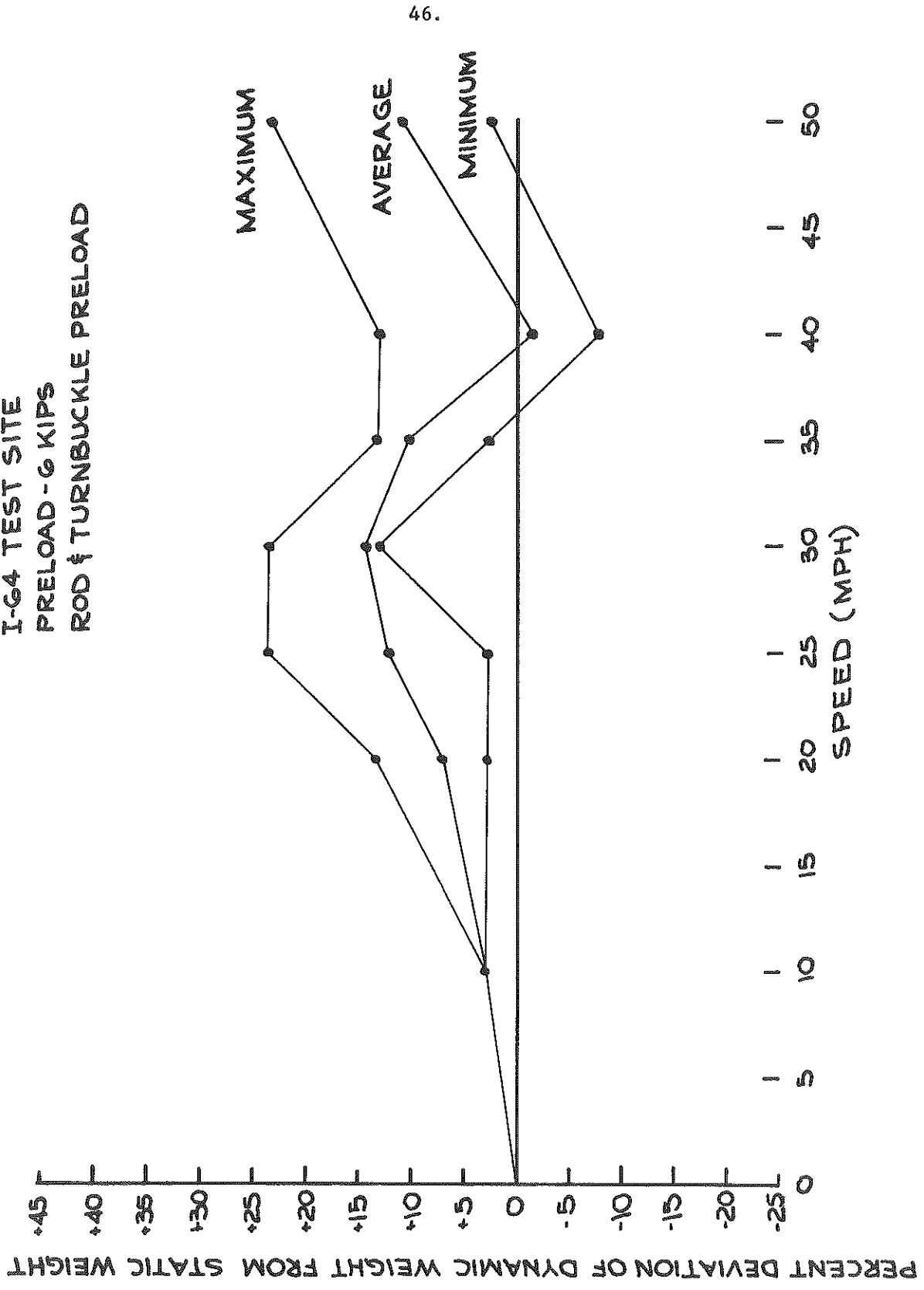


FIGURE 26.
 BROKEN BRIDGE SCALE
 TWO AXLE TEST TRUCK-FRONT AXLE
 I-64 TEST SITE
 PRELOAD - 6 KIPS
 COIL SPRING PRELOAD

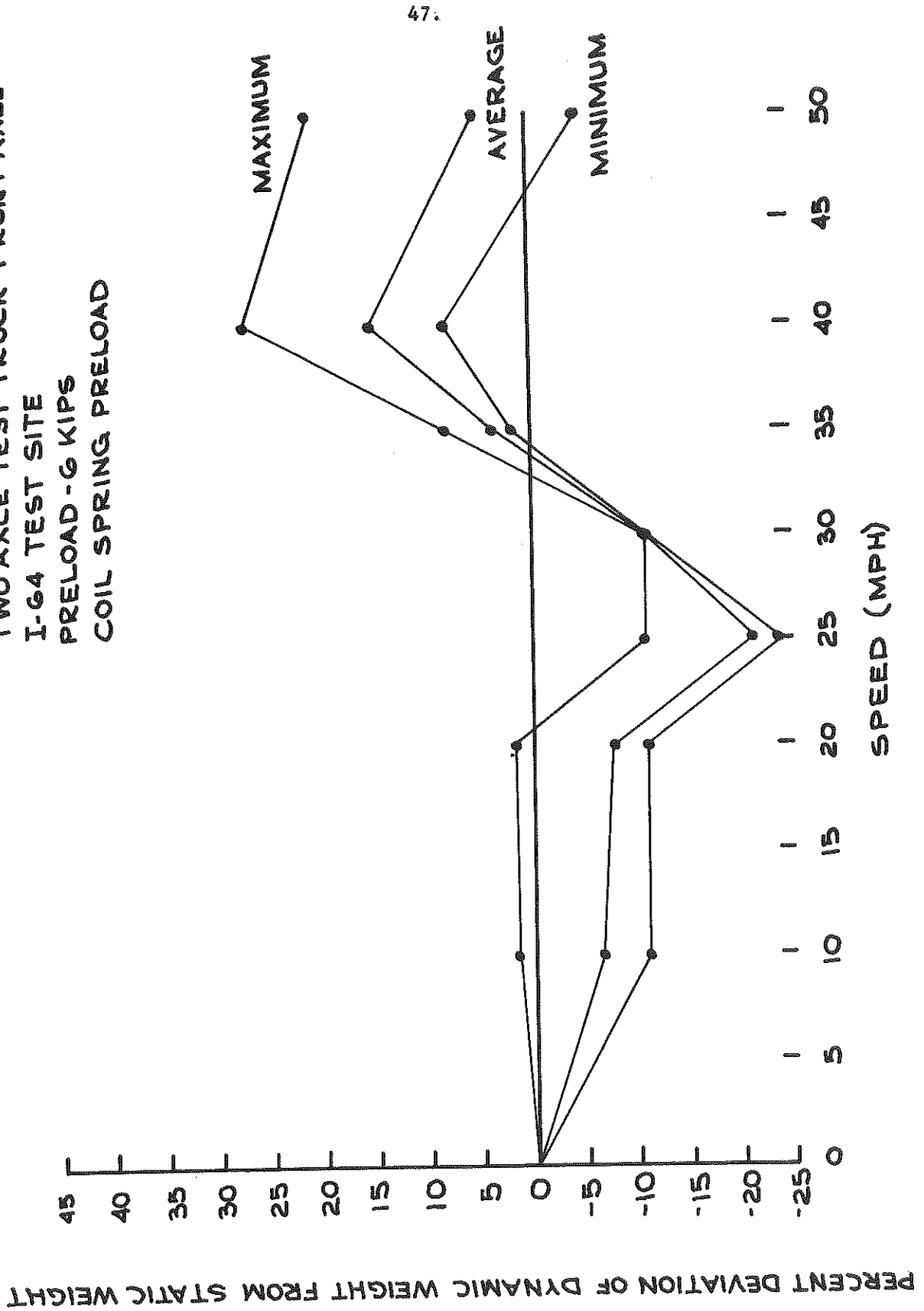


FIGURE 27.
 TALLER-COOPER SCALE
 TWO AXLE TEST TRUCK-FRONT AXLE
 I-64 TEST SITE
 12 KIP PRELOAD
 ROD & TURNBUCKLE PRELOAD

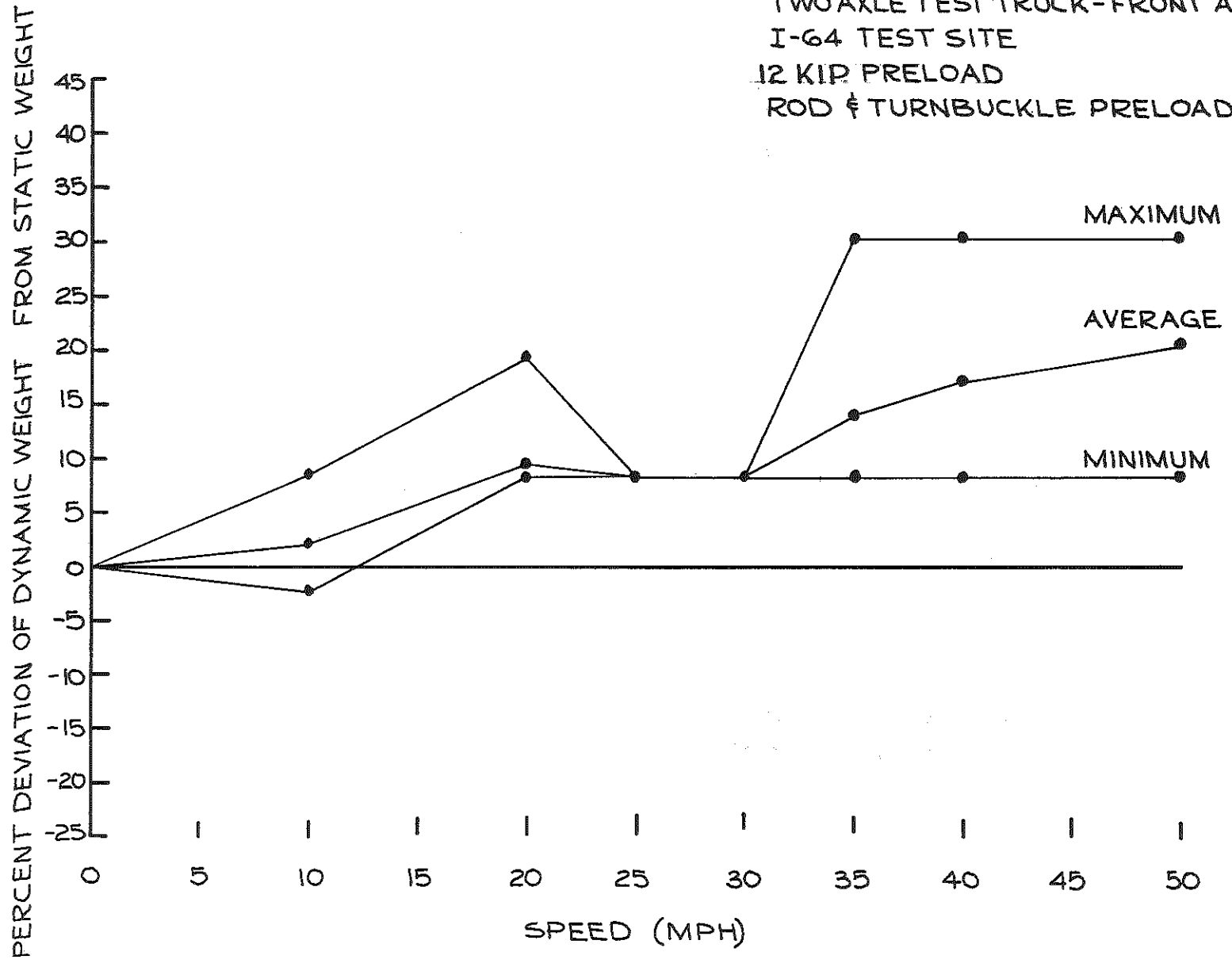
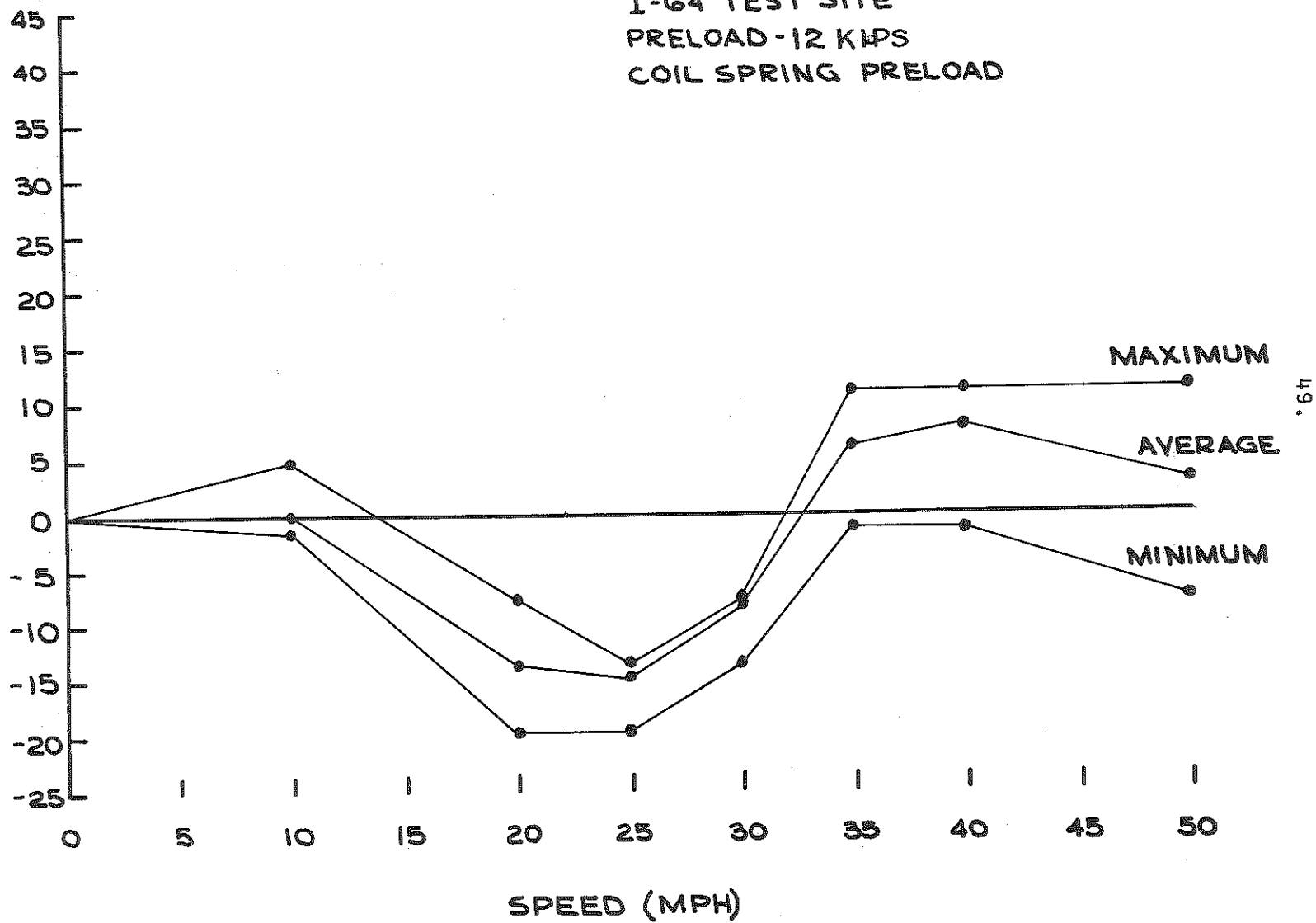


FIGURE 28.
BROKEN BRIDGE SCALE
TWO AXLE TEST TRUCK - FRONT AXLE
I-64 TEST SITE
PRELOAD - 12 KIIPS
COIL SPRING PRELOAD

PERCENT DEVIATION OF DYNAMIC WEIGHT FROM STATIC WEIGHT



64

FIGURE 29.
TALLER-COOPER SCALE
TWO AXLE TEST TRUCK-REAR AXLE
I-64 TEST SITE
PRELOAD-NONE
ROD & TURNBUCKLE PRELOAD

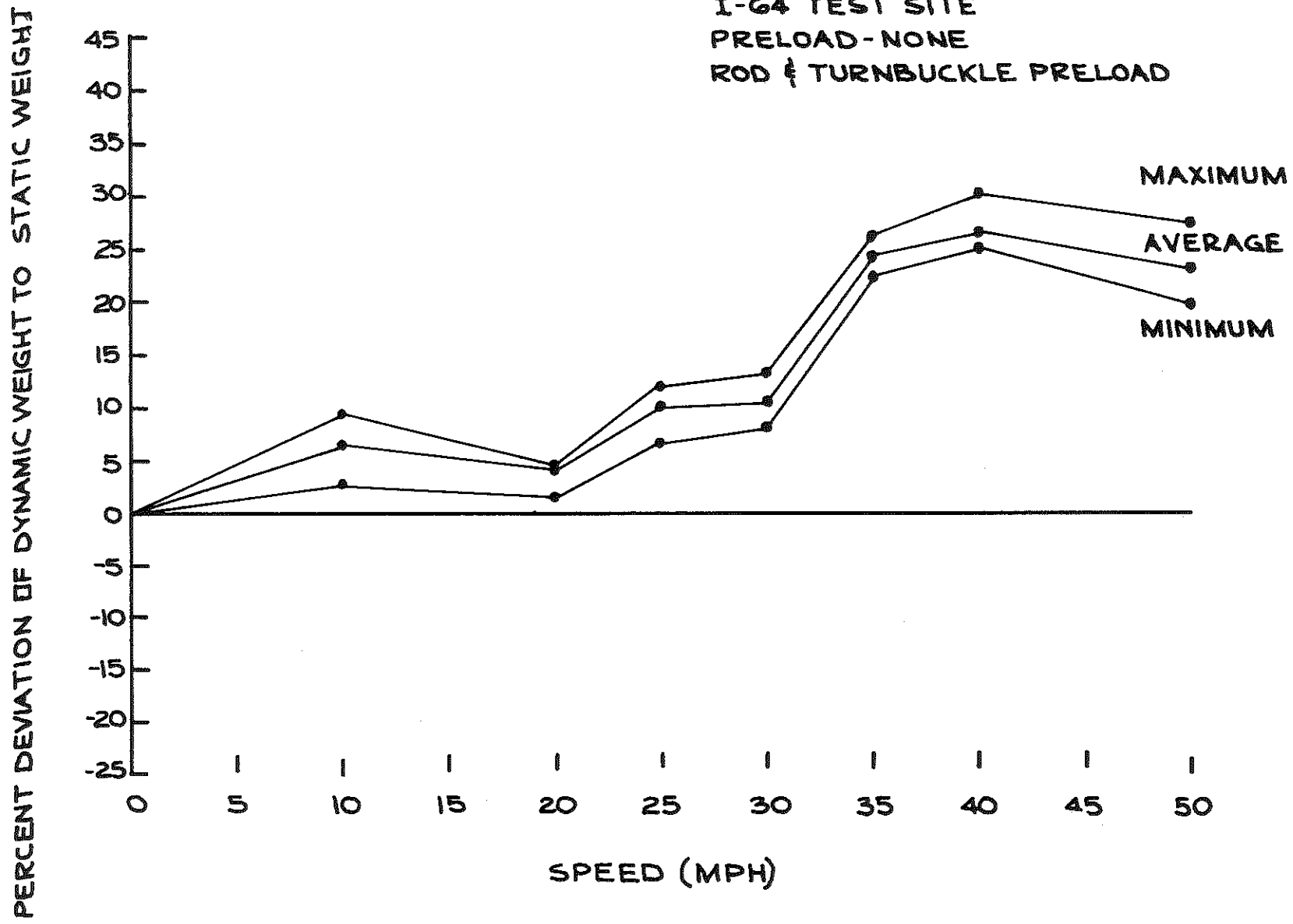
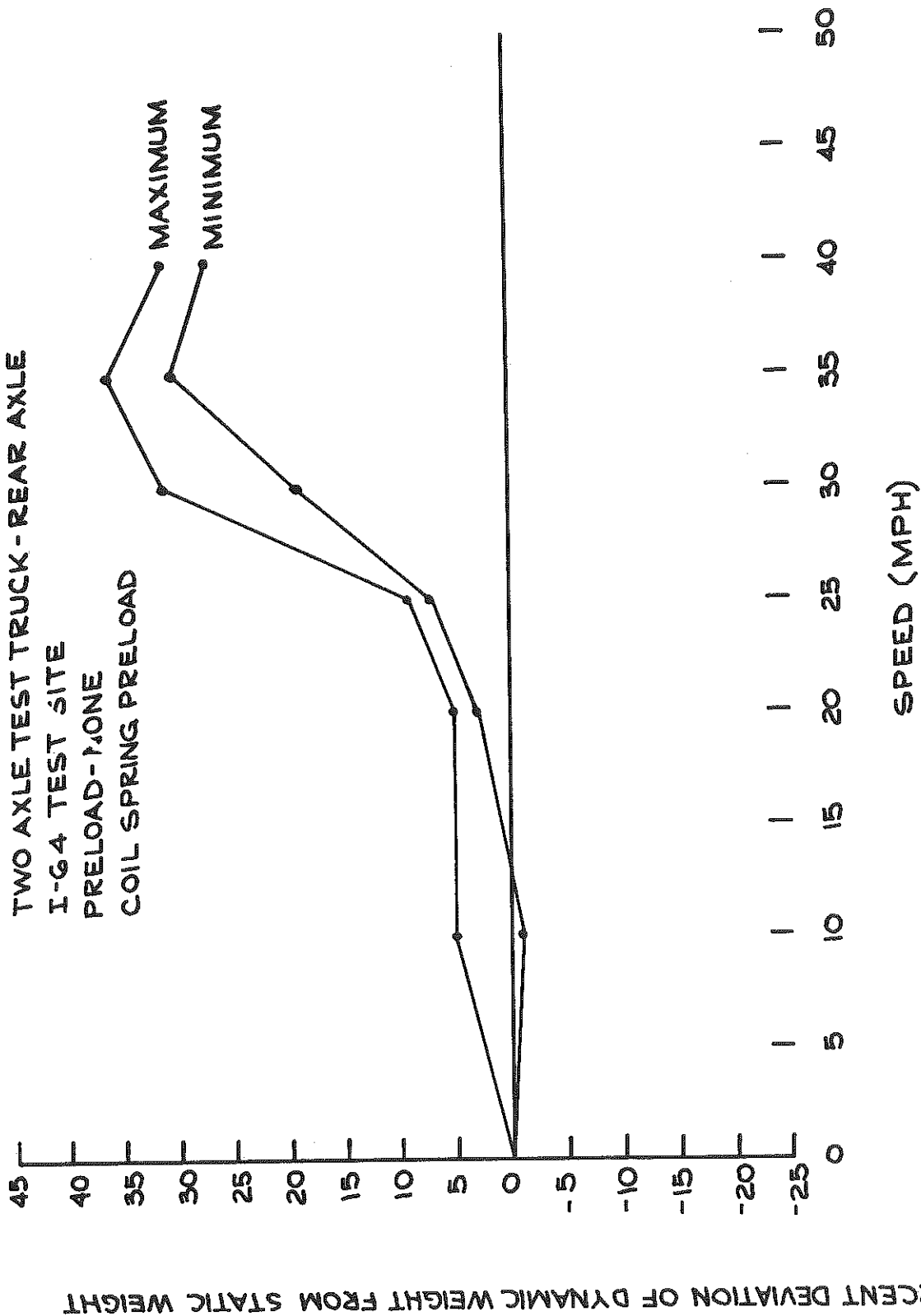


FIGURE 30.
TALLER-COOPER SCALE
TWO AXLE TEST TRUCK - REAR AXLE
I-64 TEST SITE
PRELOAD - NONE
COIL SPRING PRELOAD



PERCENT DEVIATION OF DYNAMIC WEIGHT FROM STATIC WEIGHT

SPEED (MPH)

FIGURE 31.
BROKEN BRIDGE SCALE
TWO AXLE TEST TRUCK - REAR AXLE
I-64 TEST SITE
PRELOAD - NONE
COIL SPRING PRELOAD

PERCENT DEVIATION OF DYNAMIC WEIGHT FROM STATIC WEIGHT

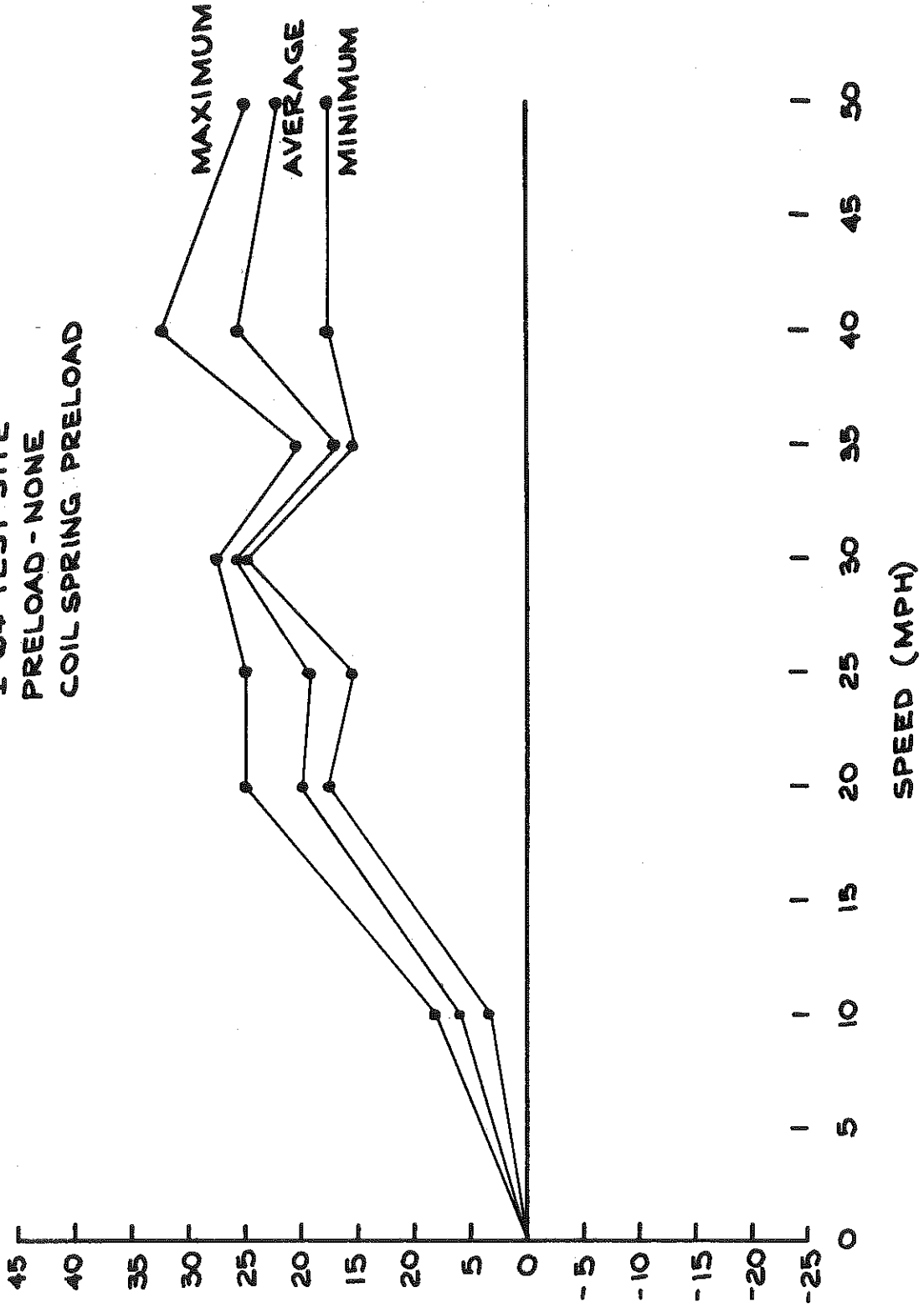


FIGURE 32.
TALLER-COOPER SCALE
TWO AXLE TEST TRUCK - REAR AXLE
I-64 TEST SITE
PRELOAD - 6 KIPS
ROD & TURNBUCKLE PRELOAD

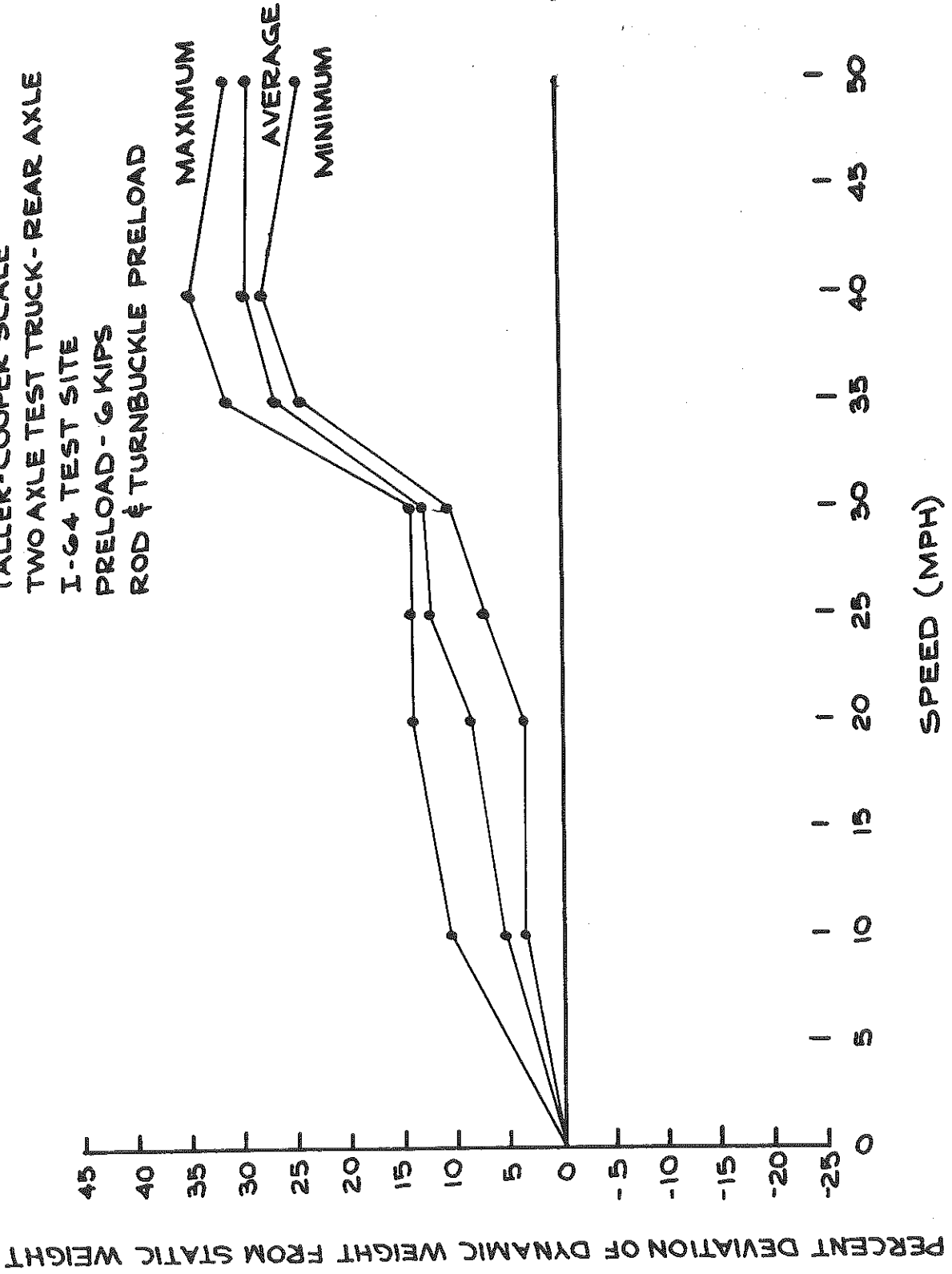


FIGURE 33.
TALLER-COOPER SCALE
TWO AXLE TEST TRUCK - REAR AXLE
I-64 TEST SITE
PRELOAD - 6 KIPS
COIL SPRING PRELOAD

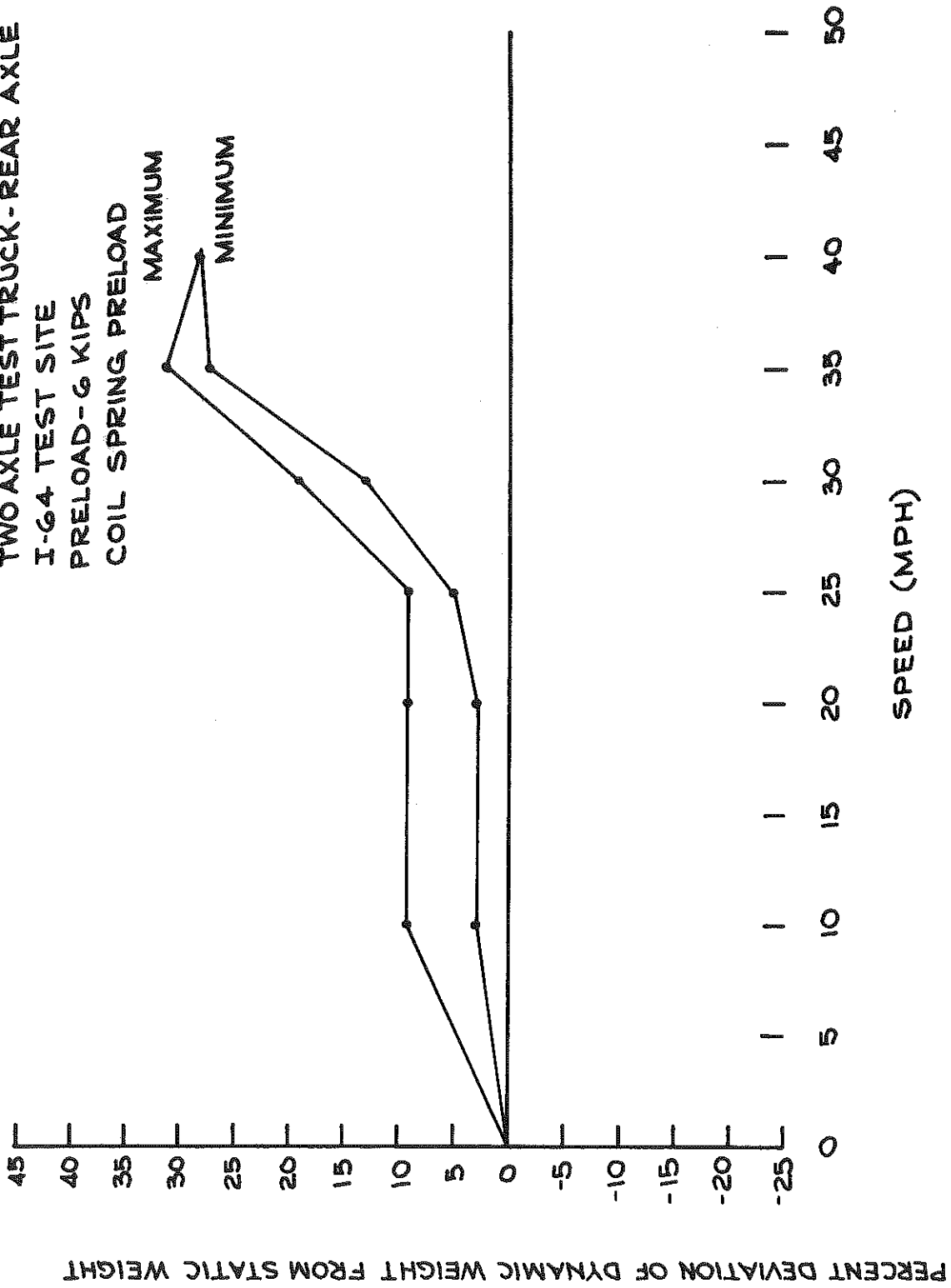
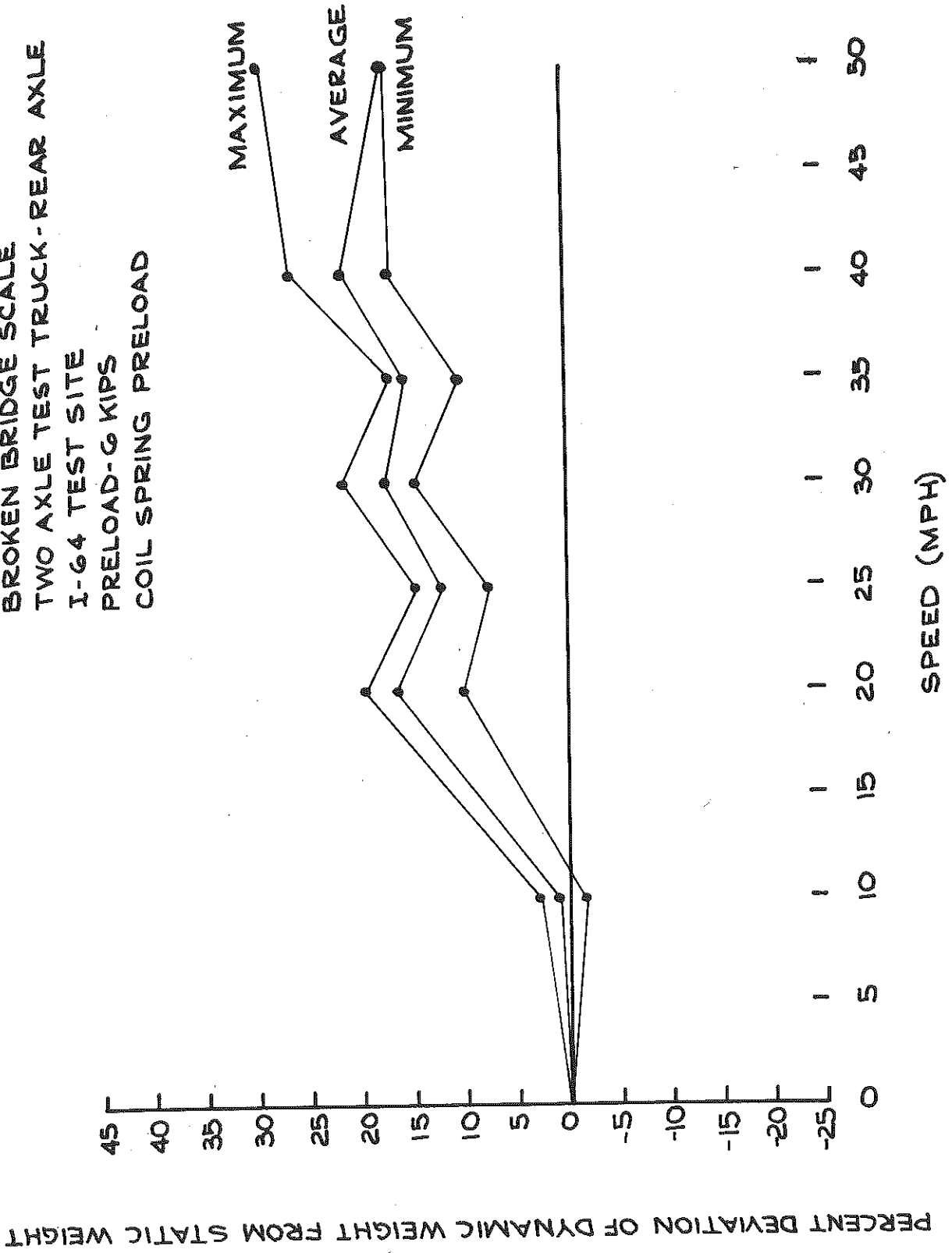


FIGURE 34.
BROKEN BRIDGE SCALE
TWO AXLE TEST TRUCK-REAR AXLE
I-64 TEST SITE
PRELOAD-6 KIPS
COIL SPRING PRELOAD



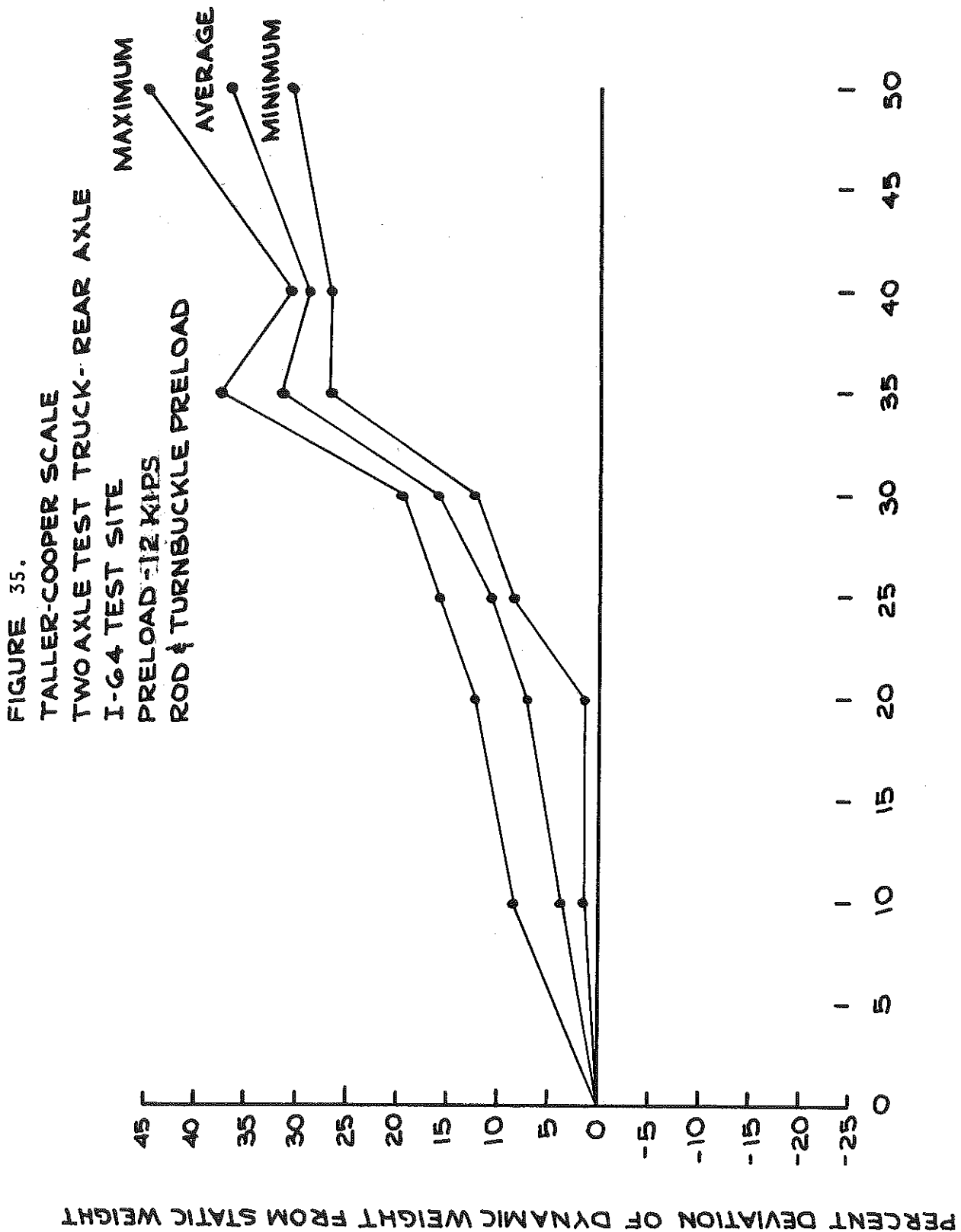
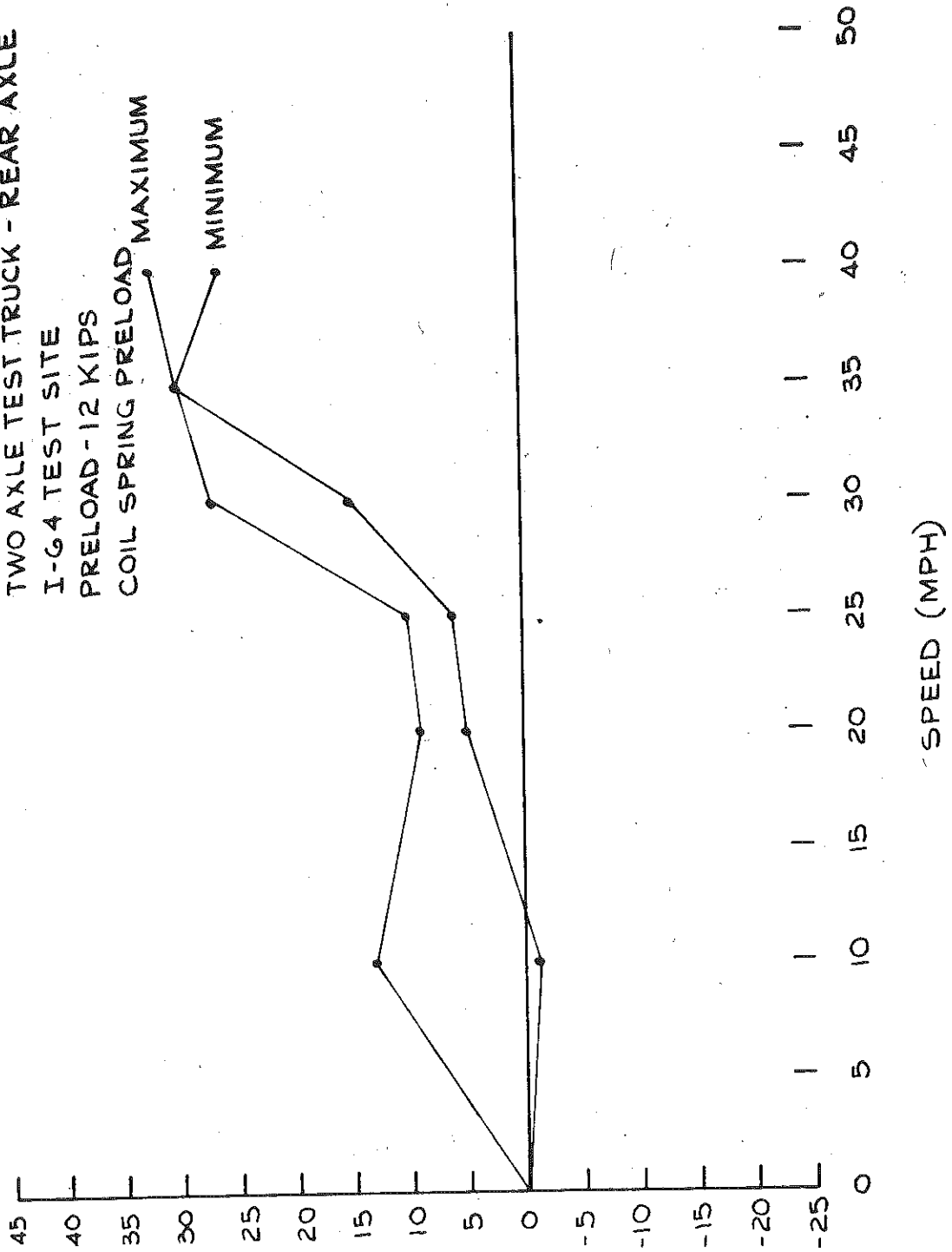


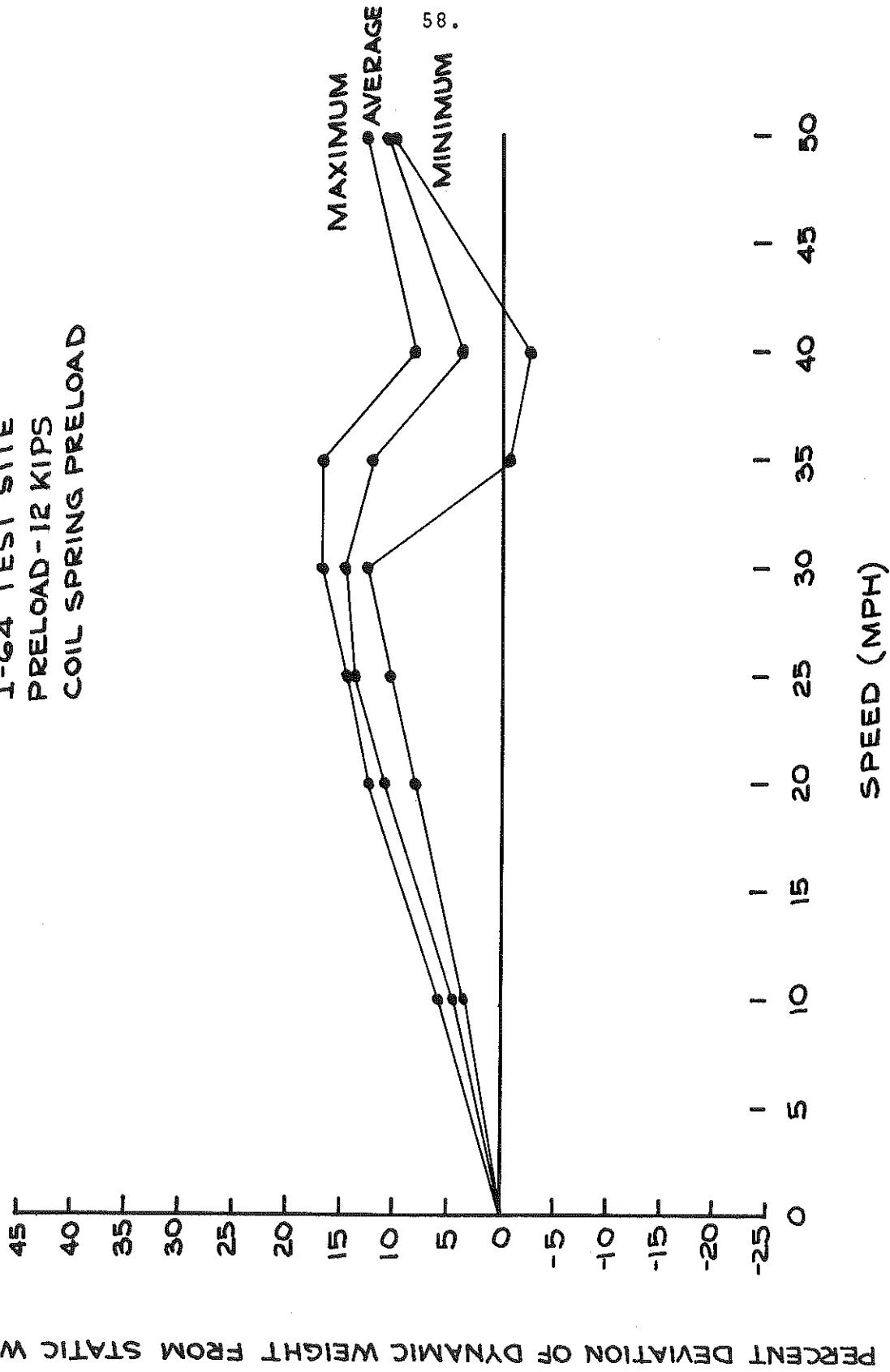
FIGURE 36.
TALLER-COOPER SCALE
TWO AXLE TEST TRUCK - REAR AXLE
I-G4 TEST SITE
PRELOAD - 12 KIPS
COIL SPRING PRELOAD
MAXIMUM
MINIMUM



PERCENT DEVIATION OF DYNAMIC WEIGHT FROM STATIC WEIGHT

SPEED (MPH)

FIGURE 37.
 BROKEN BRIDGE SCALE
 TWO AXLE TEST TRUCK-REAR AXLE
 I-64 TEST SITE
 PRELOAD-12 KIPS
 COIL SPRING PRELOAD



58.

FIGURE 38.
BEAM SCALE
TWO AXLE TEST TRUCK
I-64 TEST SITE
PRELOAD - NONE
FRONT AXLE

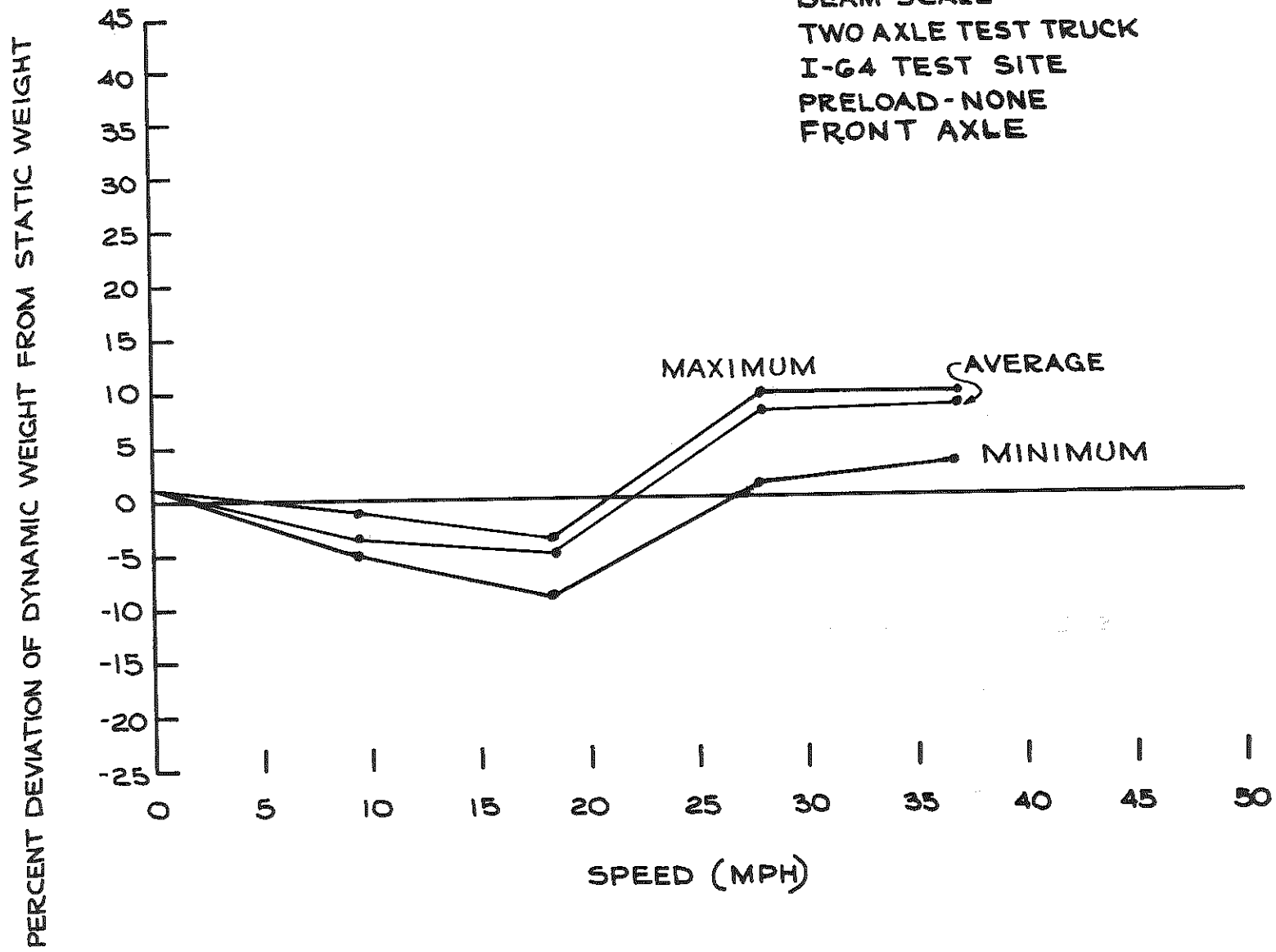
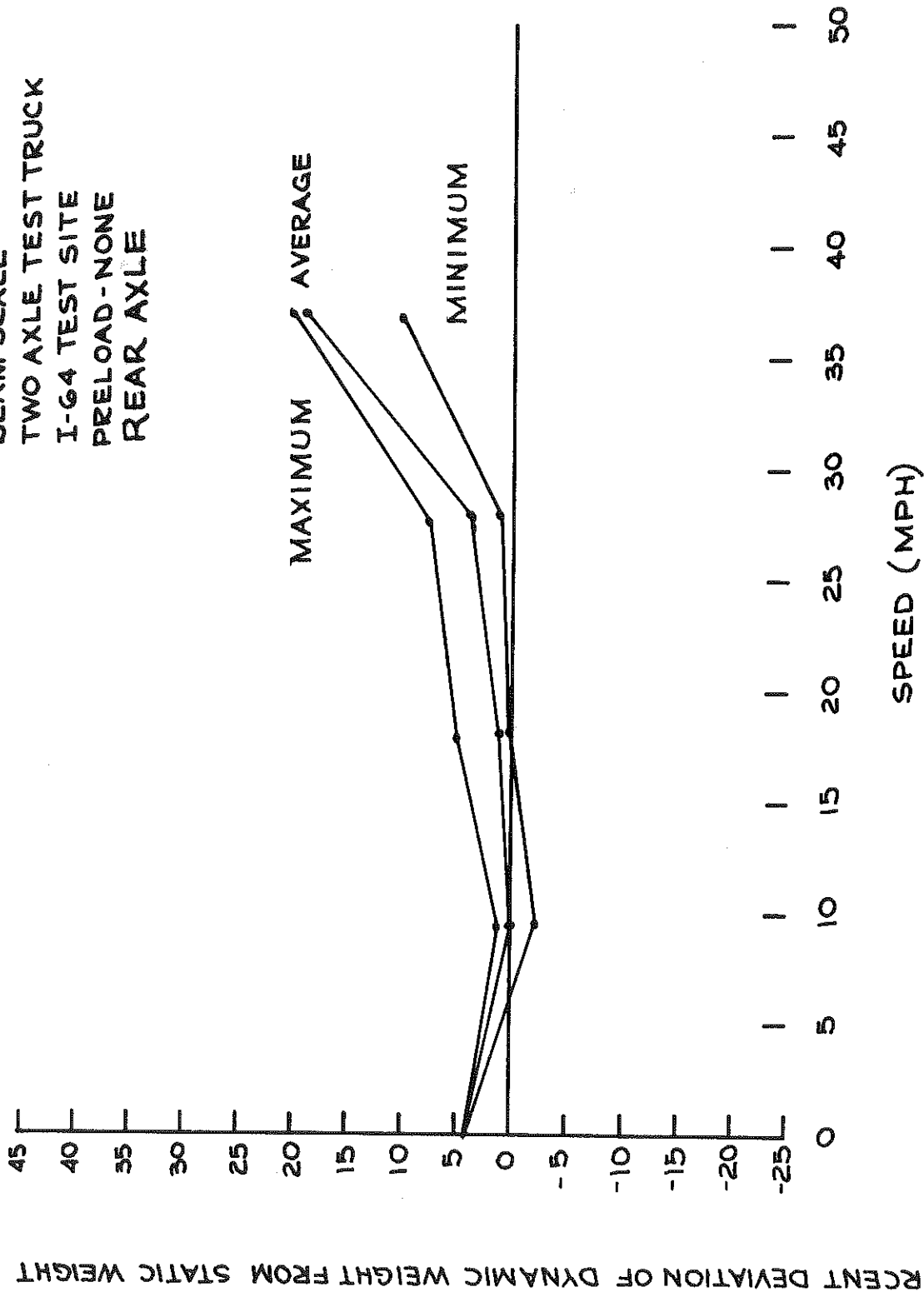


FIGURE 39.
BEAM SCALE
TWO AXLE TEST TRUCK
I-64 TEST SITE
PRELOAD - NONE
REAR AXLE



The curves of Figures 23 through 39 are strikingly similar in shape. This similarity seems to be a function of the site and the suspension system characteristics of the two axle truck - it is relatively independent of the weighing device. Subsequent experiments in measuring dynamic weight by axle housing strain and tire pressure variations served to further verify this phenomenon. (See Appendix D).

Results of Phase Two Tests at the I-64 Site.

Analysis of the random sample data collected at the I-64 test site is based on the static and dynamic weights of individual axles. The gross weight of a given truck is not considered although such information could be readily extracted from the output of the data reduction program. The analysis is concerned primarily with axle weights because in both design and enforcement applications it is regarded as the significant variable.

Percent deviations from static weight under varying conditions of preload are plotted for the Teller-Cooper (with rod and turnbuckle preload) and Broken Bridge scales in Figures 40 through 47. Figures 48 and 49 are similar presentations for the Teller-Cooper scale with coil spring preload. Figure 50 shows the results obtained for the beam scale.

For the zero and 6 kip preload conditions, the spring-stabilized Teller-Cooper scale, and for the beam scale, the plotted points are for all axles and truck types. In the remaining plots it was necessary to separate the two and three axle trucks from those with four and five axles due to the large amount of data to be represented.

The "18 kip limit line" shown on each figure illustrates the accuracy with which each of the scales could have detected the passage of axles weighing more than 18000 pounds. The line was plotted in each case by

considering that the allowable deviation for a 15 kip axle (static weight) would be 20%; for a 12 kip axle, 50%, etc.

Considerable difficulty was encountered in trying to induce the drivers of the random sample vehicle⁵ to cross the dynamic scales at reasonably high speeds. Median crossing speeds for the zero and 12 kip preload runs were, as a consequence, only about 20 mph and 23 mph respectively.

Makeup of the samples as to truck type was approximately what was anticipated from the Kentucky Highway Department's loadometer surveys of traffic on U.S. 60, the primary highway which parallels I-64. The preponderance of each truck type in the sample (272 vehicles) selected for the 12 kip preload runs was as follows:

2 axles - 25.7%

3 axles - 10.6%

4 axles - 48.2%

5 axles - 15.5%

As can be seen from Figures 40 through 49, the outstanding difference between the Tallar-Cooper scale and the Broken Bridge is that, at this particular site, the former tends to overweigh most of the axles. The pattern of plotted points for the Broken Bridge tends to center about the line of zero deviation, a situation to be expected when point samples are taken of a function (the dynamic weight) that varies with time in an approximate sinusoidal manner.

Reference to the position of the 18 kip limit line on each of the graphs reveals that any of the scales tested would have done a creditable job of culling out overloaded vehicles. To correctly compare one scale with another for this capability the sample sizes would have to be taken into account. On this basis the beam scale and the Taller-Cooper and Broken Bridge scales with zero preload would rate higher than the other configurations tested.

Table 2 summarizes the results of the random sample runs in terms of average deviations from static weight.

Table 2.

Average Percent Deviation of Dynamic Weight from Static Weight

Preload	Taller-Cooper (Rod & Turnbuckle)	Taller Cooper (Coil Spring)	Broken Bridge (Coil Spring)	Beam Type Scale
Zero	10	--	4	11
6 kips	21	27	8	--
12 kips	12 (2,3 axle)	18 (all axles)	5 (2,3 axle)	--
12 kips	18 (4,5 axle)	--	8 (4,5 axle)	--

FIGURE 40.

TALLER-COOPER SCALE
RANDOM SAMPLE-2,3,4,15 AXLE TRUCKS
ALL AXLES-ALL SPEEDS
PRELOAD-NONE

64.

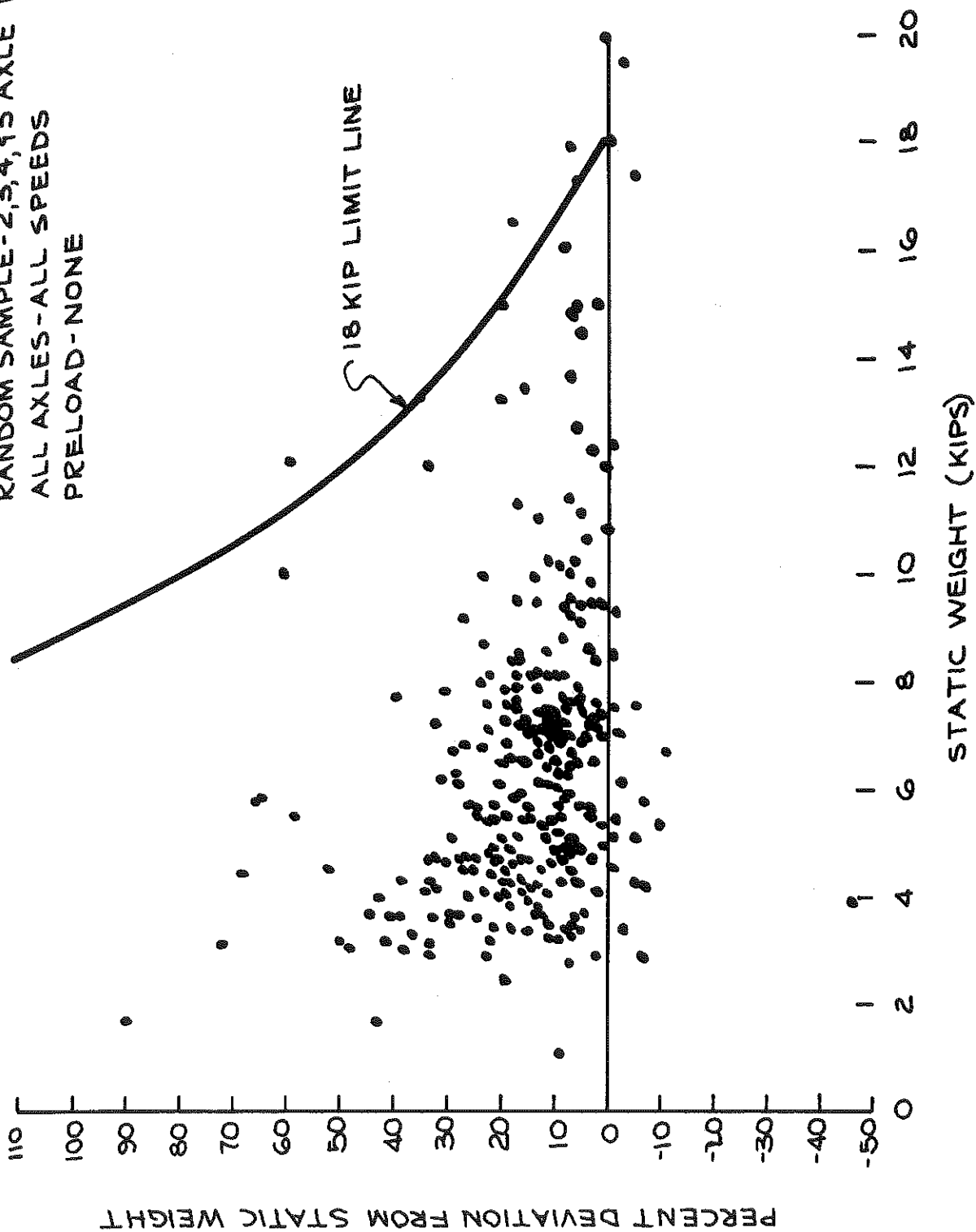


FIGURE 41.
BROKEN BRIDGE SCALE
RANDOM SAMPLE - 2,3,4, 15 AXLE TRUCKS
ALL AXLES, ALL SPEEDS
PRELOAD - NONE

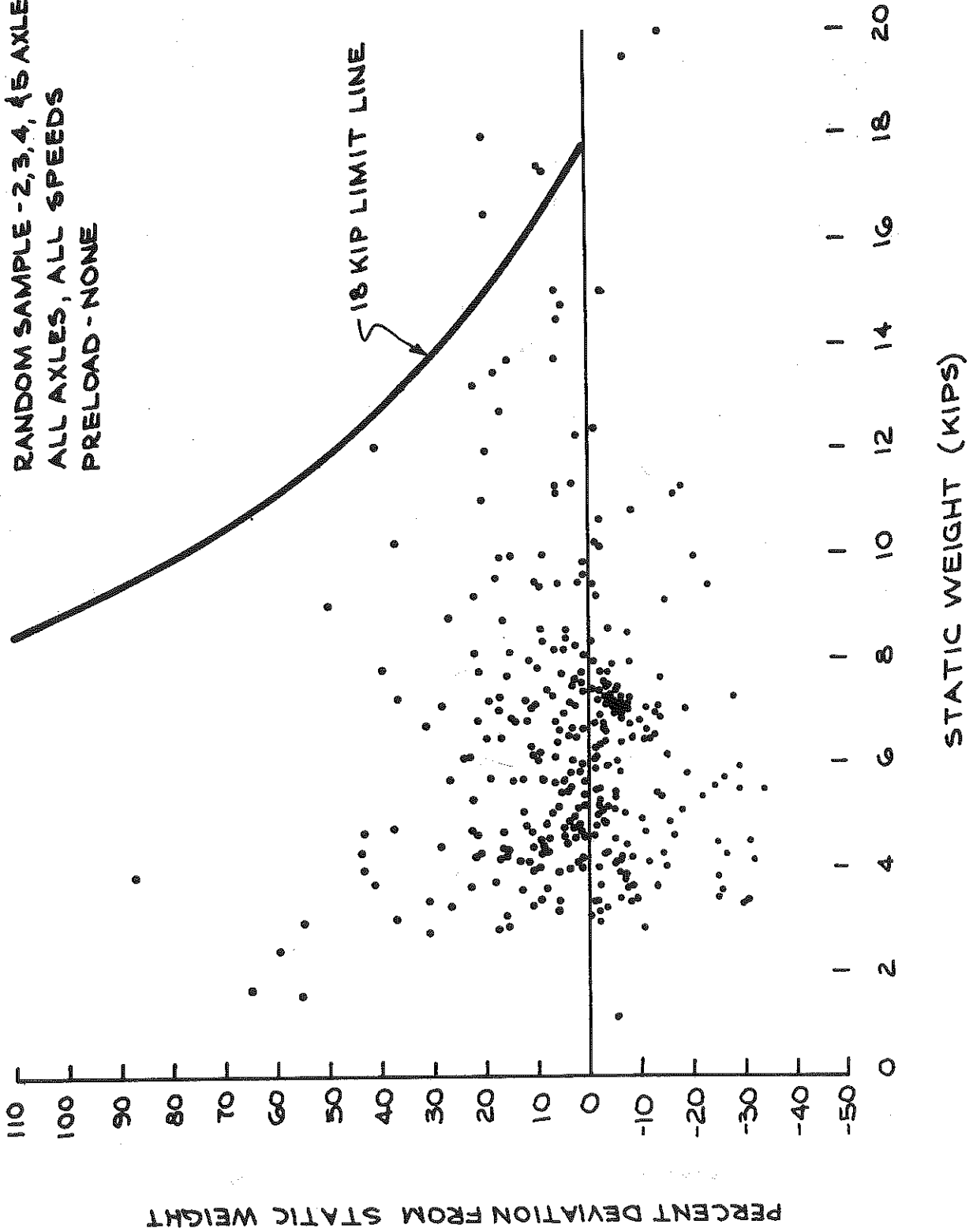


FIGURE 42.
TALLER-COOPER SCALE
RANDOM SAMPLE-2,3,4 & 5 AXLE TRUCKS
ALL AXLES - ALL SPEEDS
PRELOAD - 6 KIPS

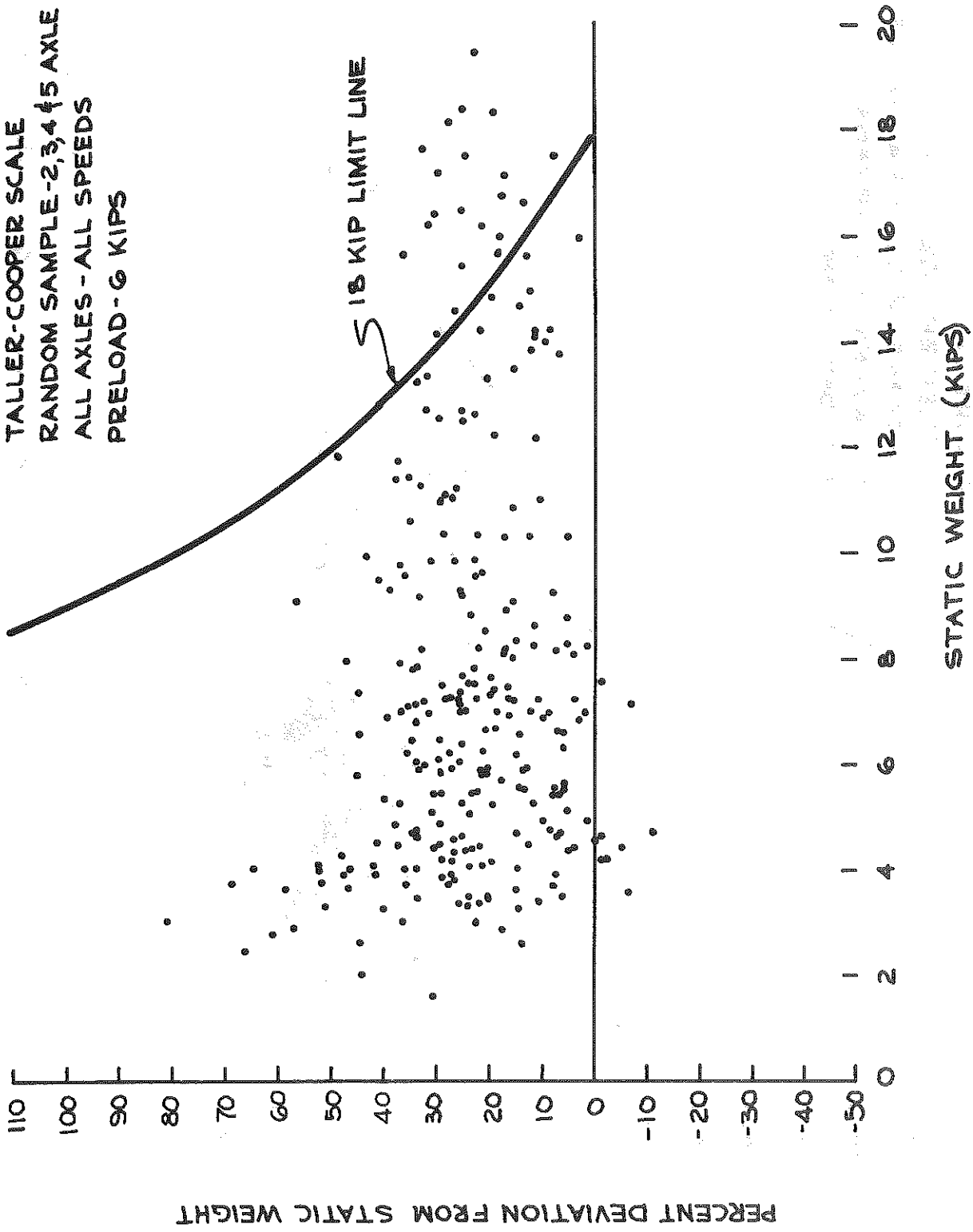


FIGURE 43.
BROKEN BRIDGE SCALE
RANDOM SAMPLE - 2, 3, 4, 5 AXLE TRUCKS
ALL AXLES - ALL SPEEDS
PRELOAD - 6 KIPS

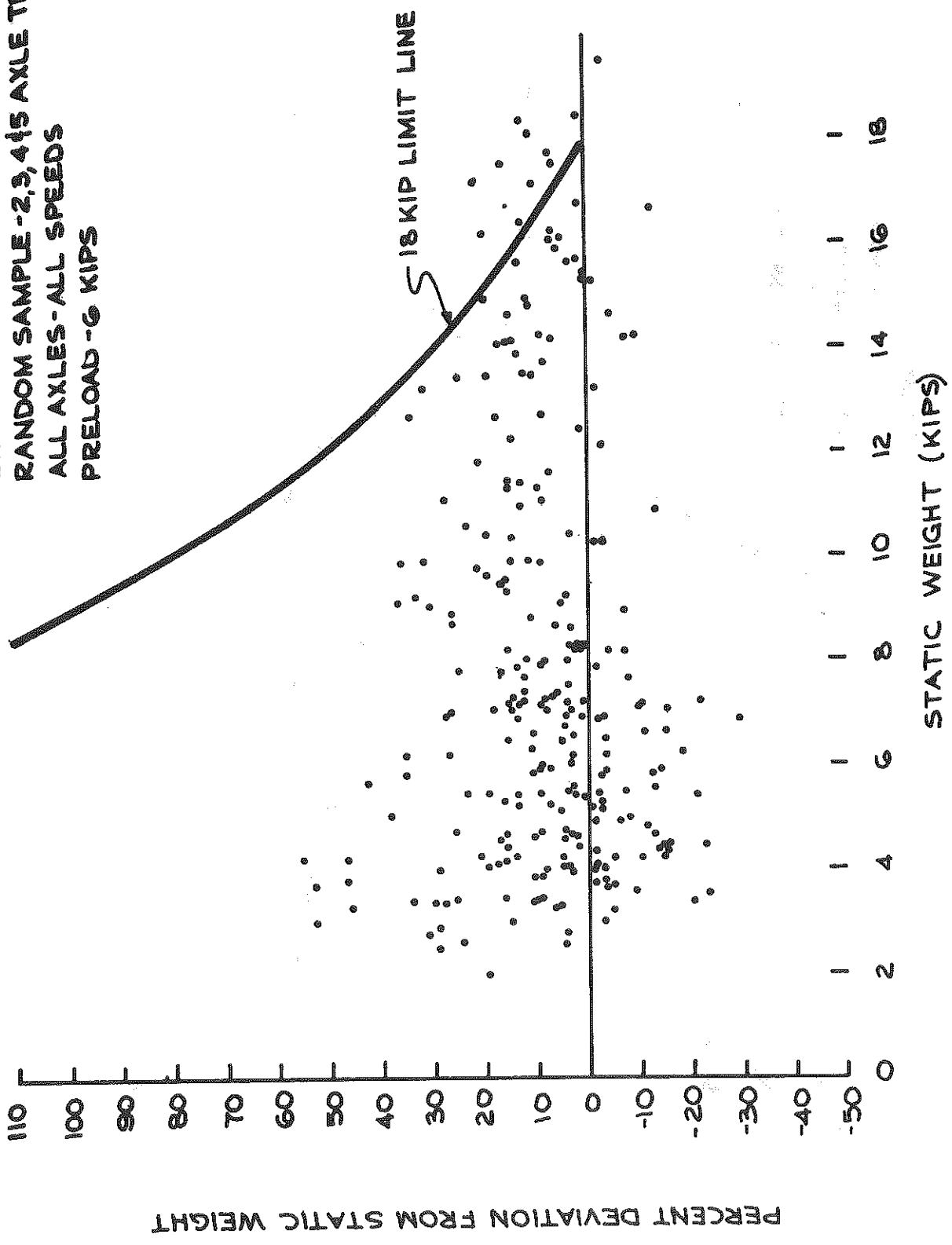


FIGURE 44.

TALLER-COOPER SCALE
RANDOM SAMPLE - 2,3,4 & 5 AXLE TRUCKS
ALL SPEEDS - 2 1/3 AXLE TRUCKS
PRELOAD - 10 KIPS

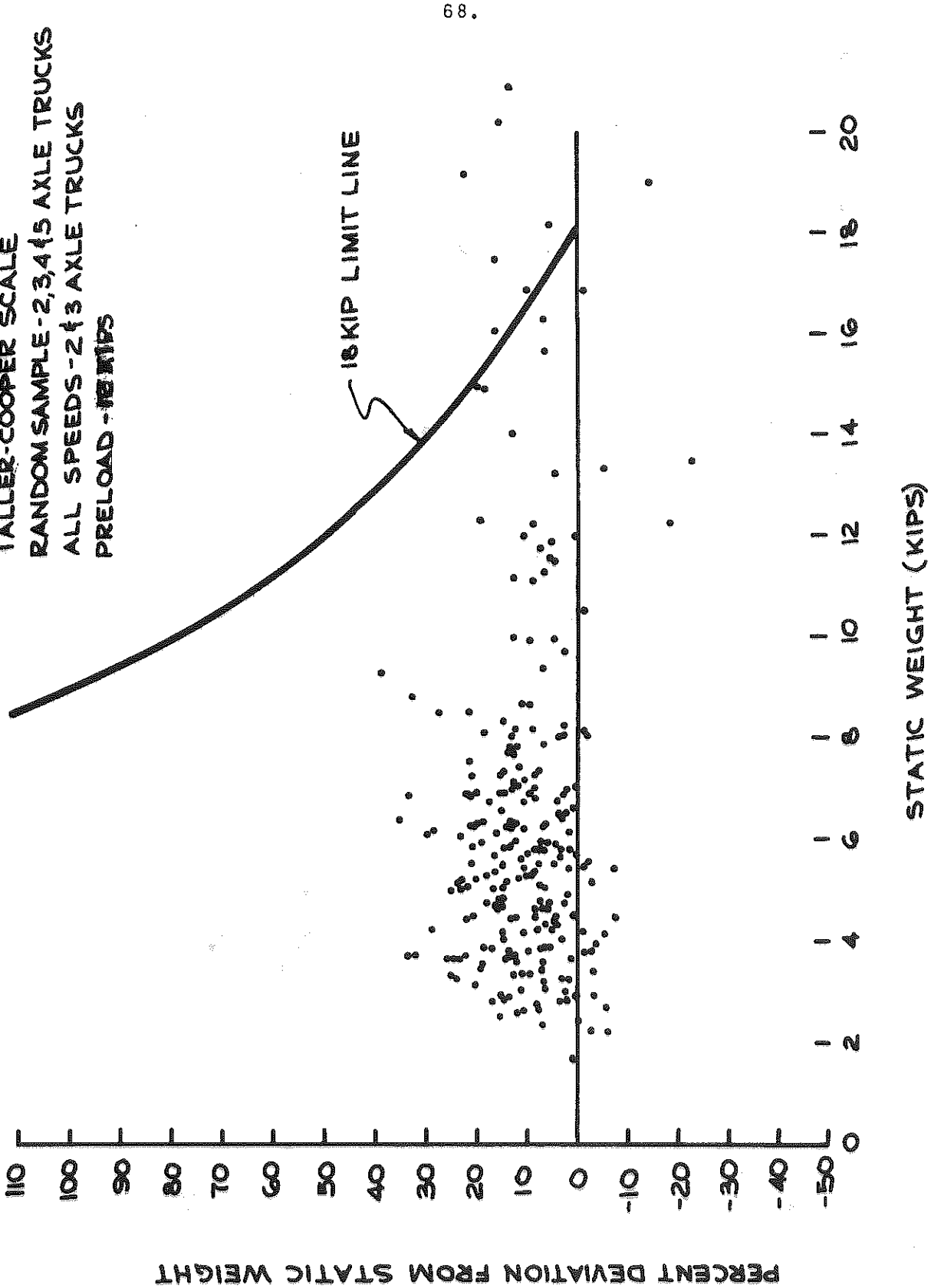


FIGURE 45.
TALLER-COOPER SCALE
RANDOM SAMPLE-2,3,4 & 5 AXLE TRUCKS
ALL SPEEDS-4 & 5 AXLE TRUCKS
PRELOAD-12 KIPS

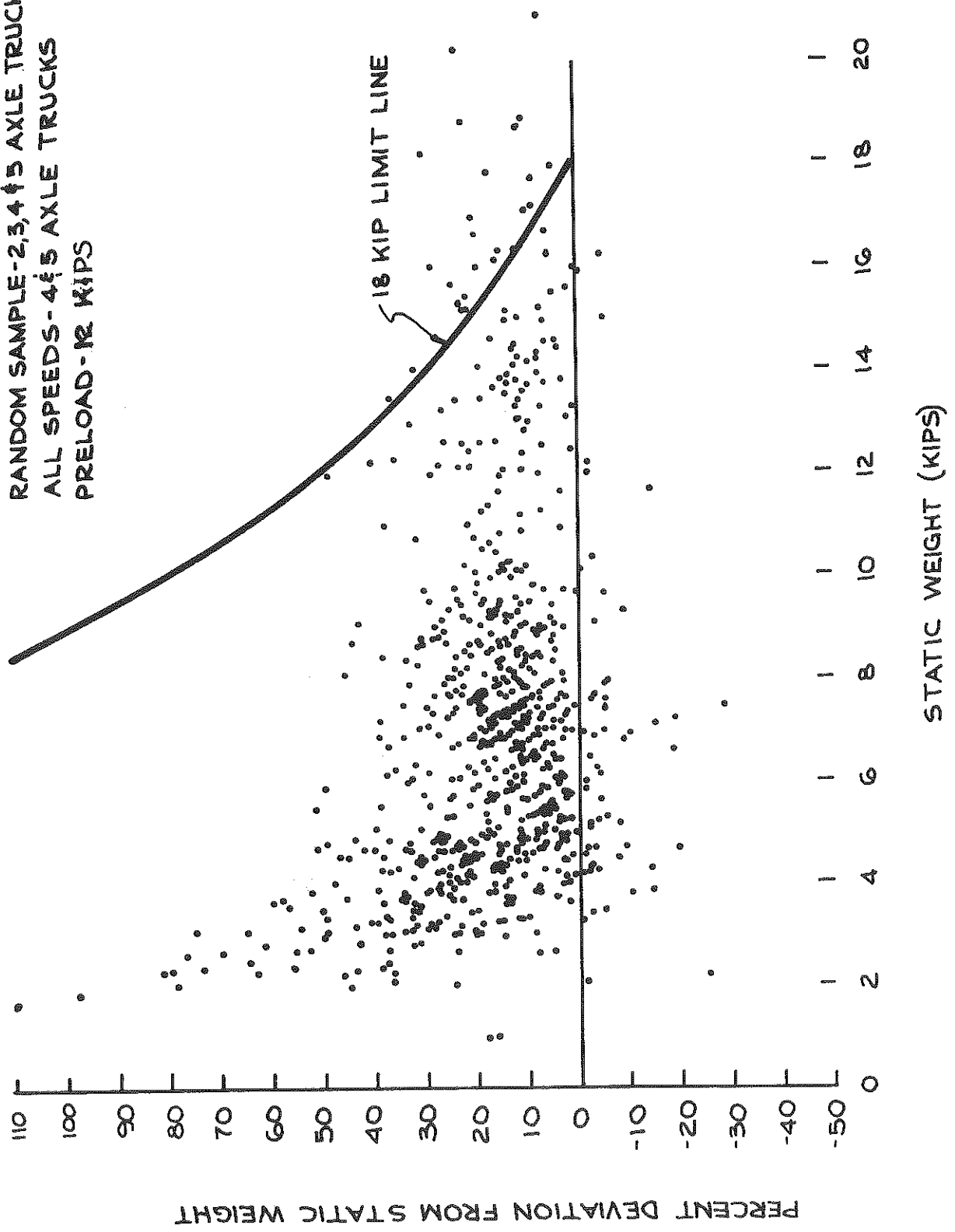


FIGURE 46.
BROKEN BRIDGE SCALE
RANDOM SAMPLE-2 & 3 AXLE TRUCKS
ALL SPEEDS-
PRELOAD-12 KIPS

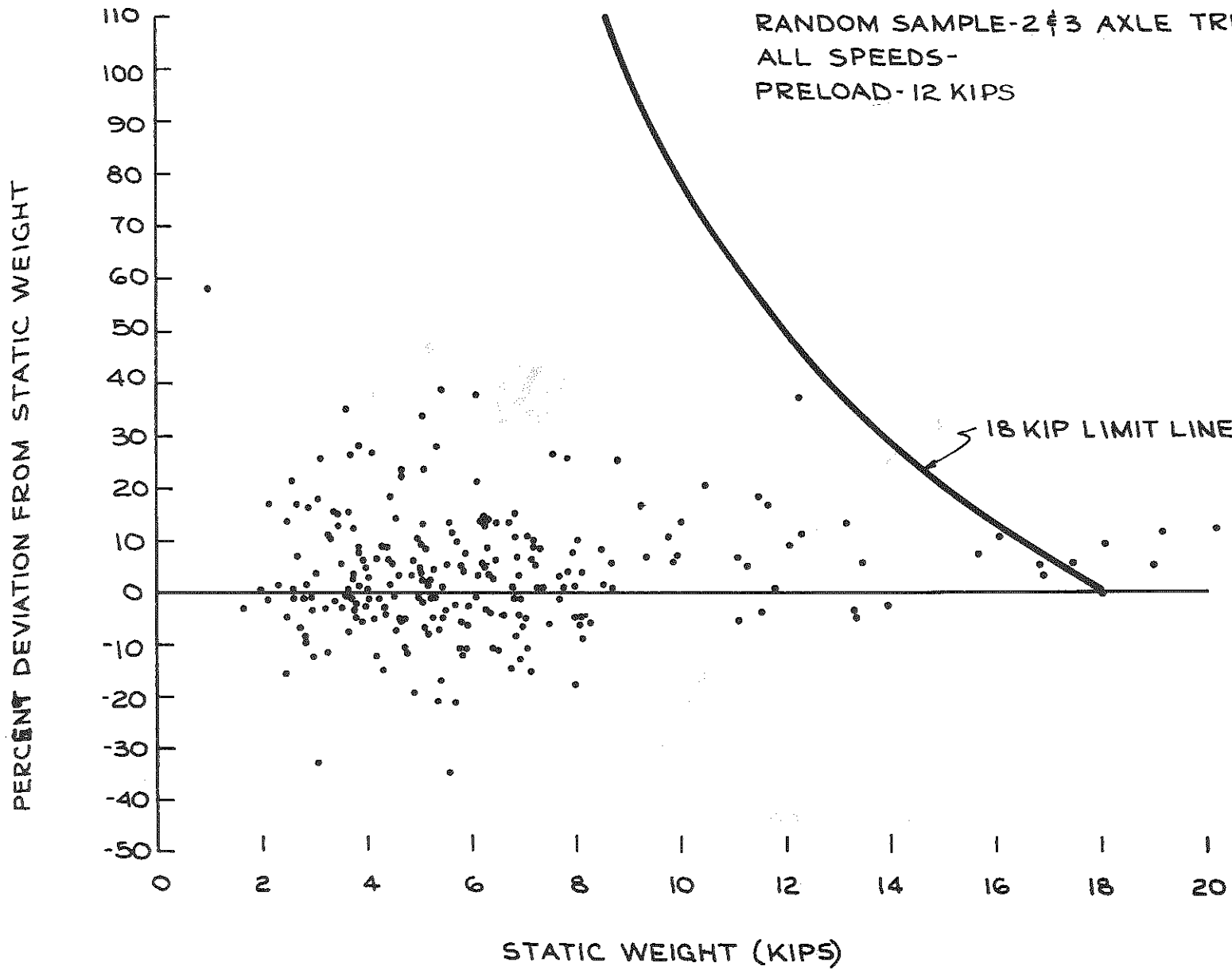


FIGURE 47.
BROKEN BRIDGE SCALE
RANDOM SAMPLE - 415 AXLE TRUCKS
ALL SPEEDS -
PRELOAD - 16 KIPS

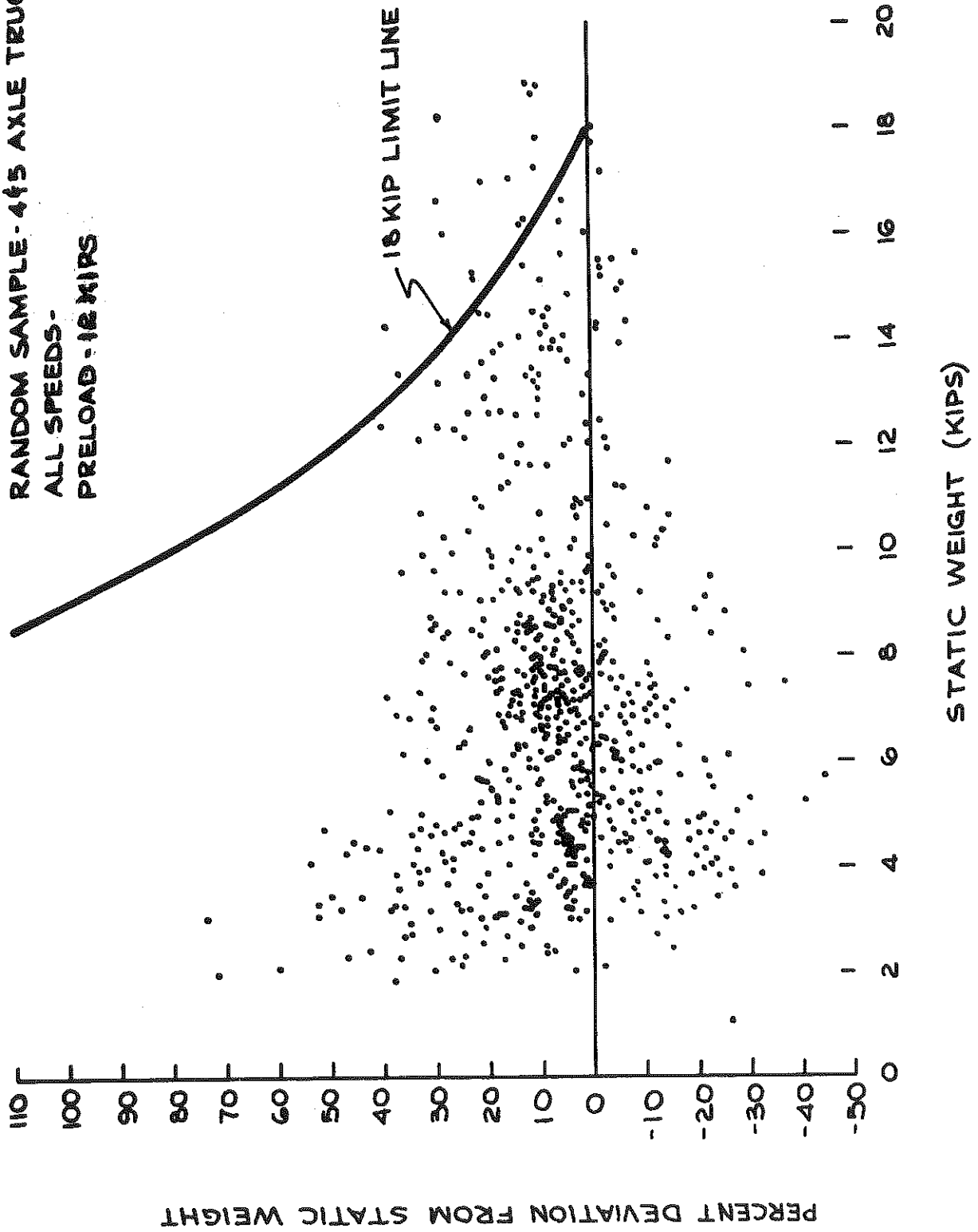
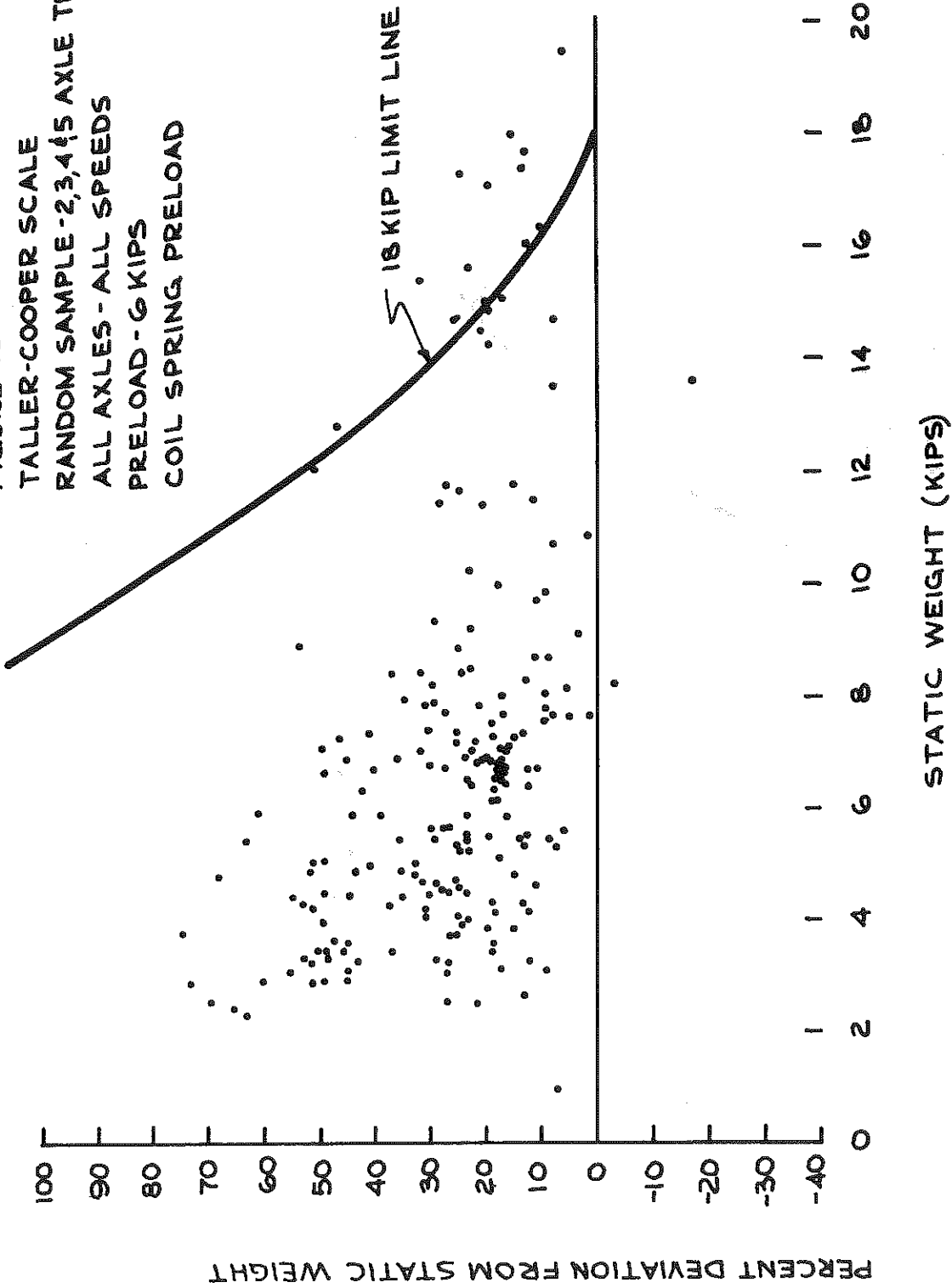


FIGURE 48.
TALLER-COOPER SCALE
RANDOM SAMPLE - 2,3,4,5 AXLE TRUCKS
ALL AXLES - ALL SPEEDS
PRELOAD - 6 KIPS
COIL SPRING PRELOAD



STATIC WEIGHT (KIPS)

PERCENT DEVIATION FROM STATIC WEIGHT

FIGURE 49.
TALLER-COOPER SCALE
RANDOM SAMPLE - 2,3,4,5 AXLE TRUCKS
ALL AXLES - ALL SPEEDS
PRELOAD - 12 KIPS
COIL SPRING PRELOAD

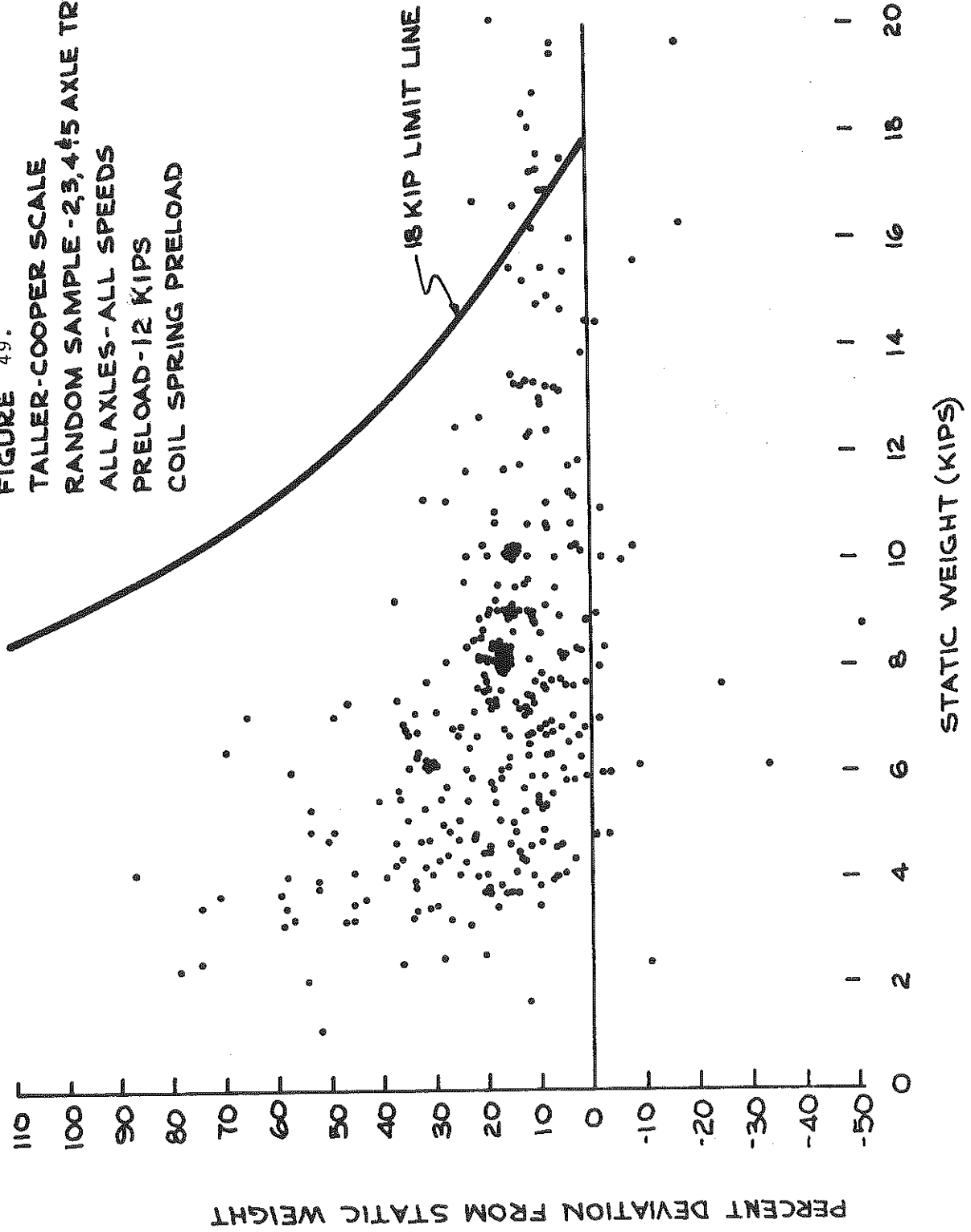
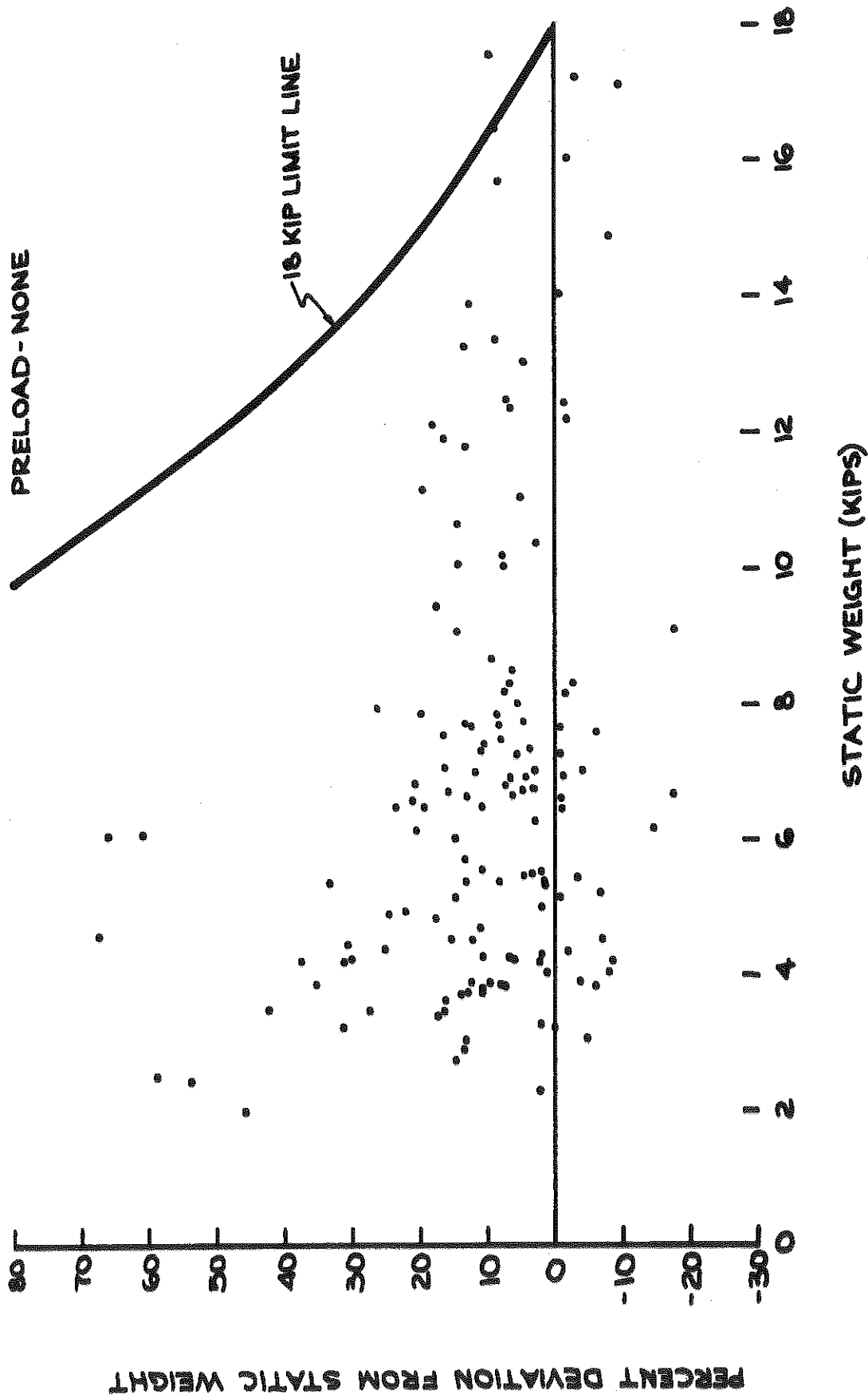


FIGURE 50.
BEAM SCALE
RANDOM SAMPLE -
ALL AXLES - ALL SPEEDS
PRELOAD - NONE



With the large amount of data available from the random sample runs it seemed advisable to investigate further the operating characteristics of the dynamic scales. All of the random sample data was used in the following analyses except the 6 kip preload runs.

A data analysis program from the IBM 1620 Program Library of the University of Kentucky Computing Center was employed to process the field measurements. This program will accept an unlimited number of X and Y pairs. In this study, X and Y represent the static and dynamic weight respectively, of a given axle. The program counts the number of pairs or observations, computes the maximum, minimum, arithmetic mean, range and standard deviation, for both X and Y, then uses these results to calculate the simple coefficient of correlation (r). By the use of a sense switch and a typed-in code number any one of six different curves may be fitted to the data previously read into the machine. Three of these curves, the straight line, hyperbola and parabola were fitted to the random sample data. The curve selected as best representing the plotted data was the straight line.

The equation of a straight line is of the form:

$$Y = A + BX$$

where, in this case,

- Y = dynamic weight (in pounds) of a given axle
- A = the intercept (in pounds) on the Y axis
- B = the slope of the straight line
- X = static weight (in pounds) of the same axle.

The significance of these symbols is that, if the dynamic and static weights were the same for each axle; A would be zero, B would be unity (1.0) and the coefficient of correlation would be unity (1.0). Deviation from this ideal forms the basis of comparison for analyzing the relative effects of speed, preload, etc. on scale performance.

The standard error of estimate was also computed for each straight line fit. This statistic is a measure of the scatter of the original data

points about the fitted curve. It may be obtained from the formula:

$$S_{y.x} = S_y \sqrt{1-r^2}$$

where,

$S_{y.x}$ = the standard error of estimate (in pounds)
 S_y = the standard deviation of the dynamic weights
 r = coefficient of correlation

About two thirds of all the original data points will lie within $\pm S_{y.x}$ of the fitted curve. Practically all (99.7%) of the points will lie within $\pm 3 S_{y.x}$ of the curve. Thus the smaller the value of the standard error of estimate the more closely the equation of the fitted curve represents the relationship between X and Y.

Figures 51 through 91 show graphically the results of the data analysis. The graphs (except those for the beam type scale) compare:

(1) two scale types (Taller-Cooper and Broken Bridge) under the same preload (Figures 51-55 and 66-71),

(2) the results obtained for the same scale at high and low speed ranges under a constant preload (Figures 56-65 and 72-81) and

(3) the results obtained for the Taller-Cooper scale under an identical preload applied by two different devices (Figures 82-86).

Results for the beam scale are shown separately in Figures 87-91.

Comparisons are made first for all axles, then separately for each individual axle location. Comparisons were omitted where the number of axles in the category was too small to yield significant results. The relative performance of the scale is in each instance represented by a plot of the straight line that was fitted to the data by the computer program. The equation of this line (known as the "regression line") is

shown on each graph as are N , the sample size and r , the coefficient of correlation. Since two regression lines are plotted on each graph, the individual data points and the boundaries of the standard error of estimate were omitted to avoid the confusion of overlapping lines and points. A tabulation of the data analysis output (including the standard errors) for each combination studied is in Appendix F.¹

In Figures 51 through 55, the principal difference between the Taller-Cooper and Broken Bridge scales at zero preload is reflected in the constant term of the regression line equations. In each case, this value is positive for the Taller-Cooper and negative for the Broken Bridge - a logical outcome of their previously noted tendencies to overweigh and underweigh the applied loads (see page 62). When compared on the basis of a static 10 kip axle load, the differences in the dynamic loads computed from the paired equations (disregarding the constant term) are within the probable tape reading error for all except the second axles. In other words, there is a more or less constant difference between the dynamic weights as measured by the two scales.

The effect of crossing speed on the unstabilized scales was, as indicated by the differences in regression line slopes, more pronounced for the Broken Bridge scale than the Taller-Cooper, particularly for the all-axle, front axle and second axle correlations (Figures 56-65). For third axles, both scales were affected by the higher speeds with the Taller-Cooper showing the greatest slope difference. The analyses of the fourth and fifth

¹The results listed in the "all speeds" column of Tables 17, 18, 19, 20 and 22 for fourth and fifth axles combined are not represented by corresponding regression line plots. The data for Figures 55, 70, 71 and 86 are not tabulated in Appendix F.

axles combined yielded high correlation coefficients and similar slopes for the Taller-Cooper scale in both speed brackets; the Broken Bridge was slightly more erratic.

The addition of a 12 kip preload to each of the scales (by rod and turnbuckle on the Taller-Cooper and by coil springs on the Broken Bridge) resulted in an increase in slope for all regression lines (Figures 66-70). Differences in intercepts remained about the same as in the zero preload condition except for front axles; here the intercepts are negative for both scales. An additional comparison for a sample of 42 fifth axles (Figure 71) shows the flatter regression line slope for the Broken Bridge and a high value of r for each scale.

The effect of crossing-speed is less evident for the heavily preloaded scales than for the unstabilized condition (Figures 72-81). The graphs for the Taller-Cooper scale show the all-axle, second axle and fourth and fifth axle regression lines to be nearly identical for the two speed categories. Some improvement may also be noted in the performance of the Broken Bridge scale though it is not as significant as it is with the Taller-Cooper.

Large differences in sample size (N) affect somewhat the validity of the comparisons between the two methods of preloading the Taller-Cooper scale (Figures 82-86) but general trends may at least be inferred from the paired plots. For each axle location the regression line slope was decreased and the intercept was increased by the change from rod and turnbuckle to coil springs. The correlation coefficient (r) remained about the same for all axles except the front, for which there was a decided decrease with the use of the coil springs preload.

An examination of the regression line plots and the tabulated data for the beam type scale seems to indicate that it is a very stable weighing

device. For example, variations in regression line slopes for the four axle categories varied from 0.953 (for fourth and fifth axles) to 1.010 (for third axles). This compares favorably with the Taller-Cooper scale and is, in most instances, better than the Broken Bridge. The closest approach to an actual agreement between static and dynamic weights was attained with the beam scale for front axles (regression line slope = 1.004). A very close agreement was also obtained for the third axles - the most erratic category for the other two scales.

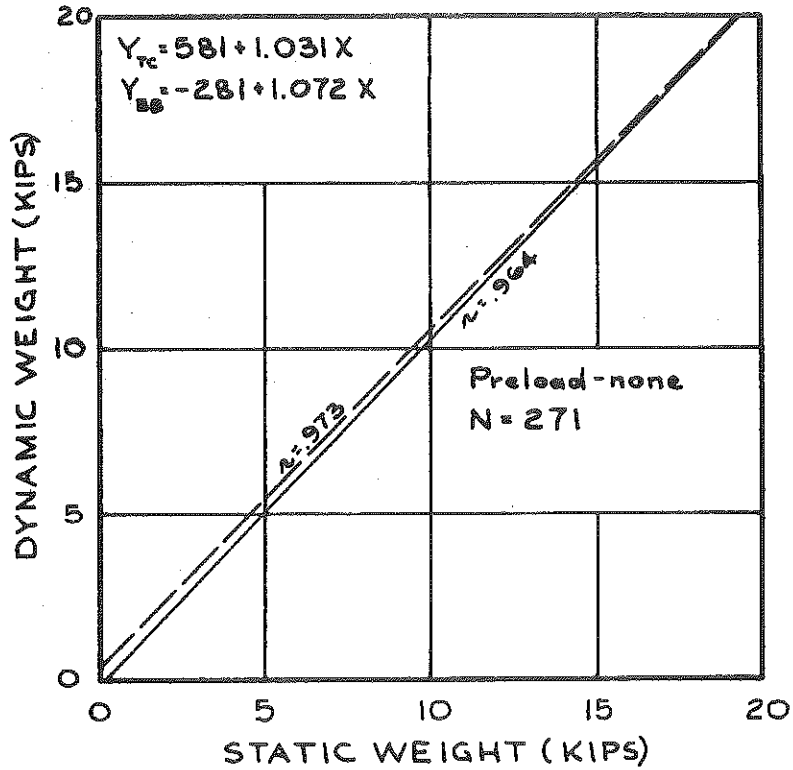


FIGURE-71. CORRELATION OF STATIC & DYNAMIC WEIGHTS,
ALL AXLES

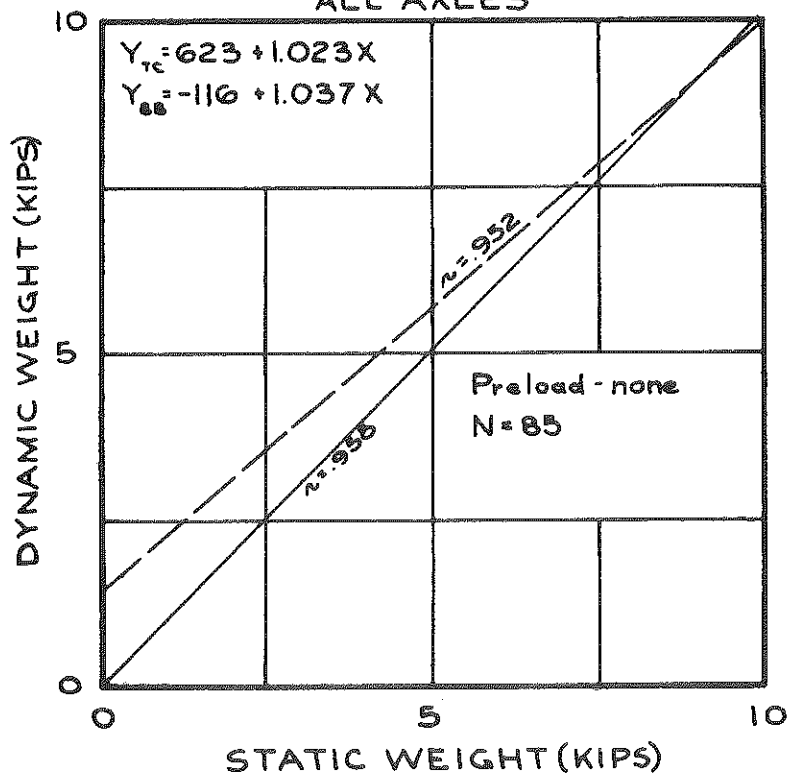


FIGURE-72. CORRELATION OF STATIC & DYNAMIC WEIGHTS,
ALL FRONT AXLES

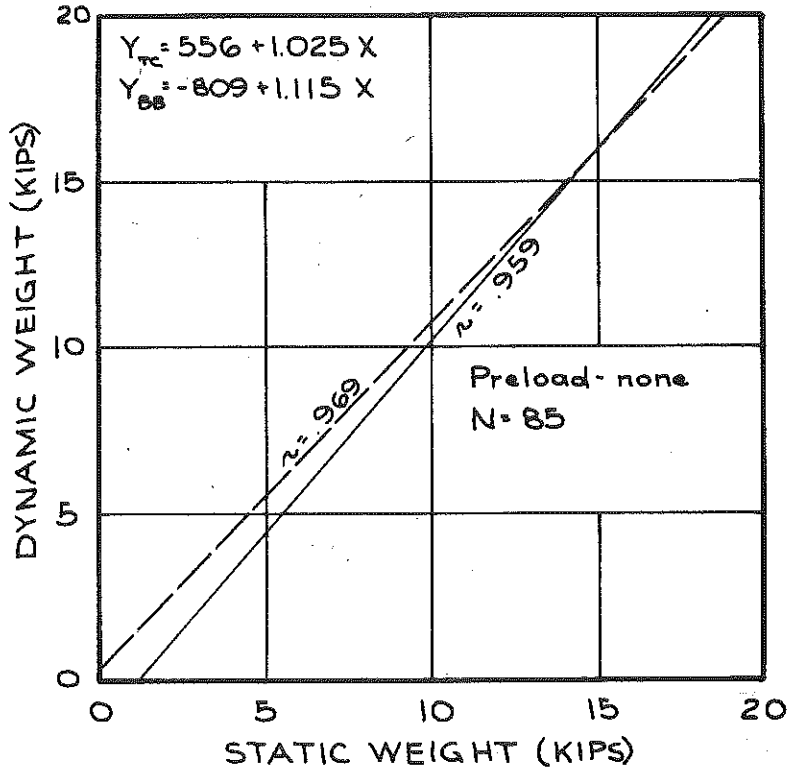


FIGURE 53. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL SECOND AXLES

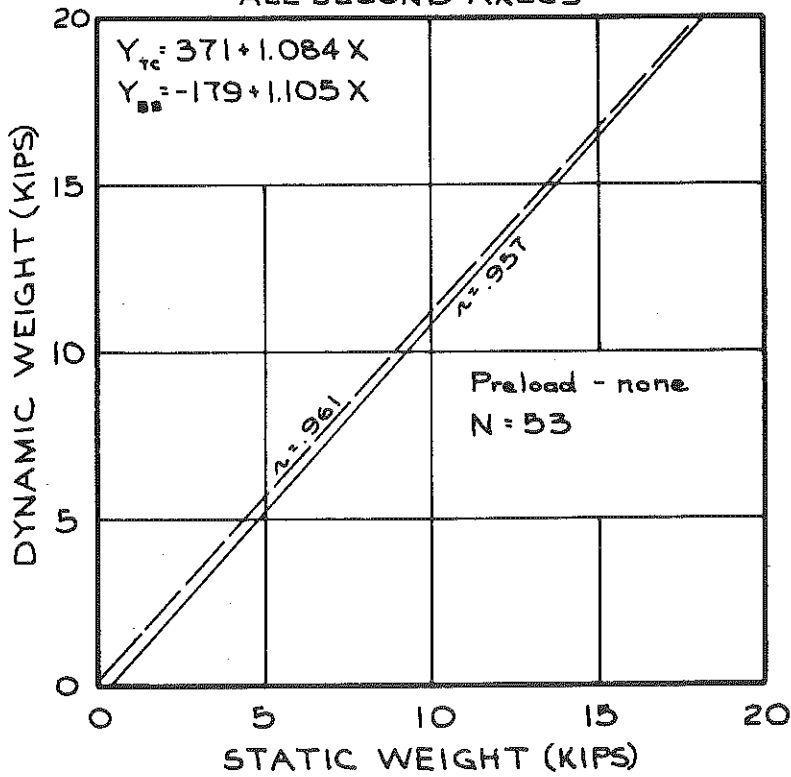


FIGURE 54. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL THIRD AXLES

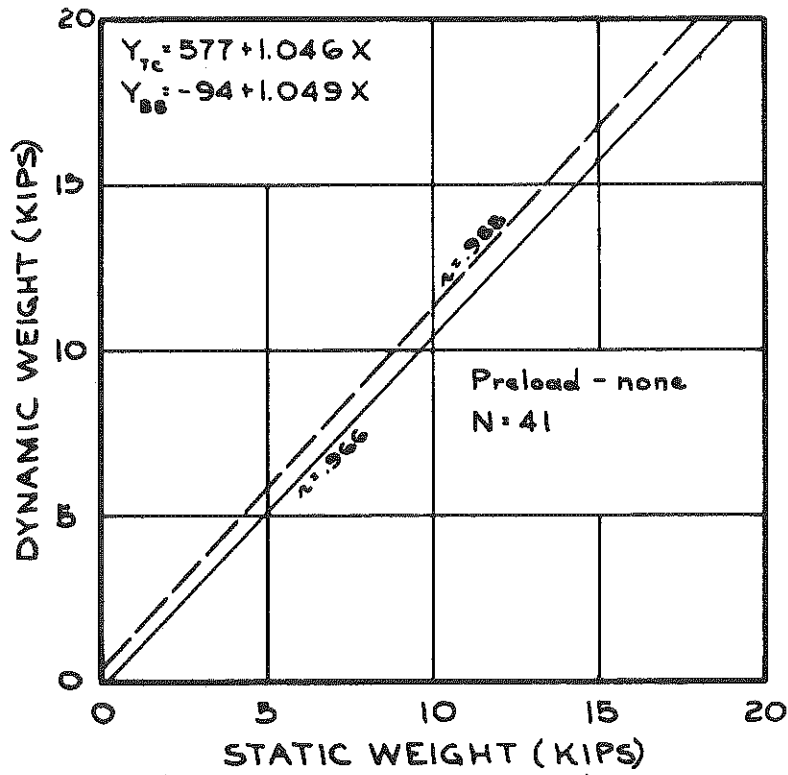


FIGURE 55 CORRELATION OF STATIC & DYNAMIC WEIGHTS,
ALL FOUR AXLES

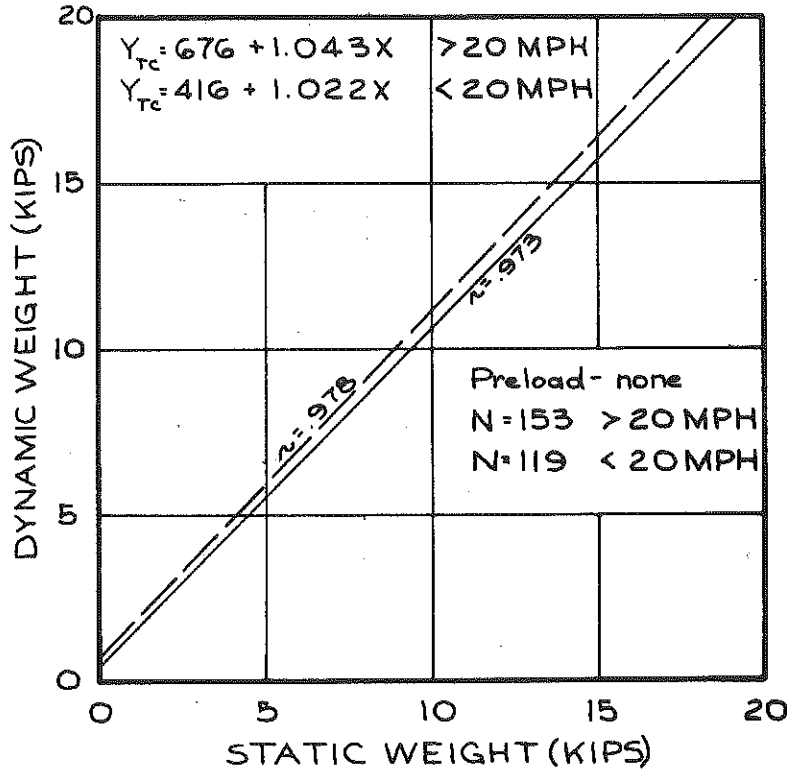


FIGURE 56. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS - ALL AXLES

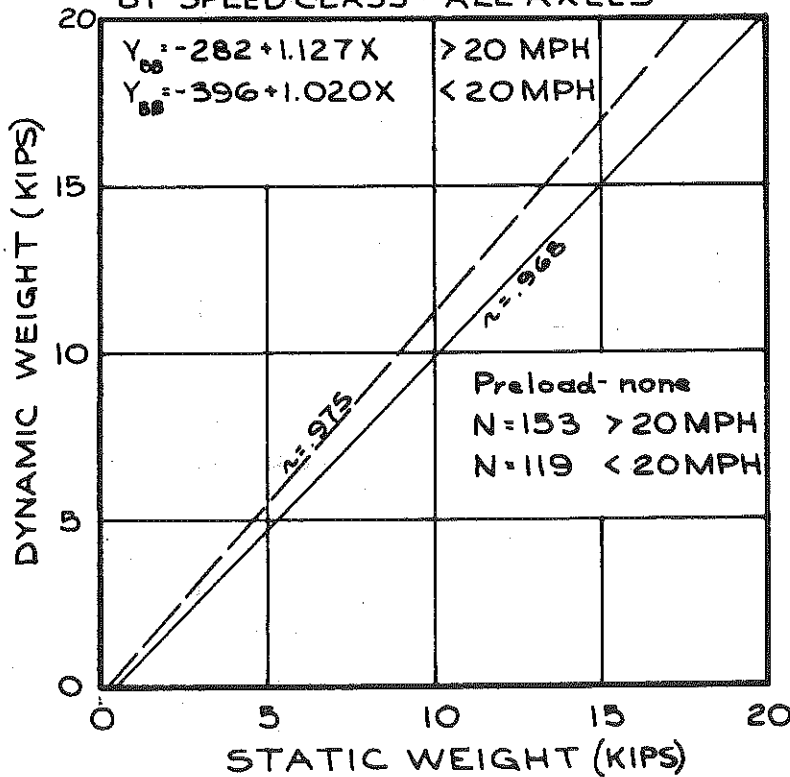


FIGURE 57. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS - ALL AXLES

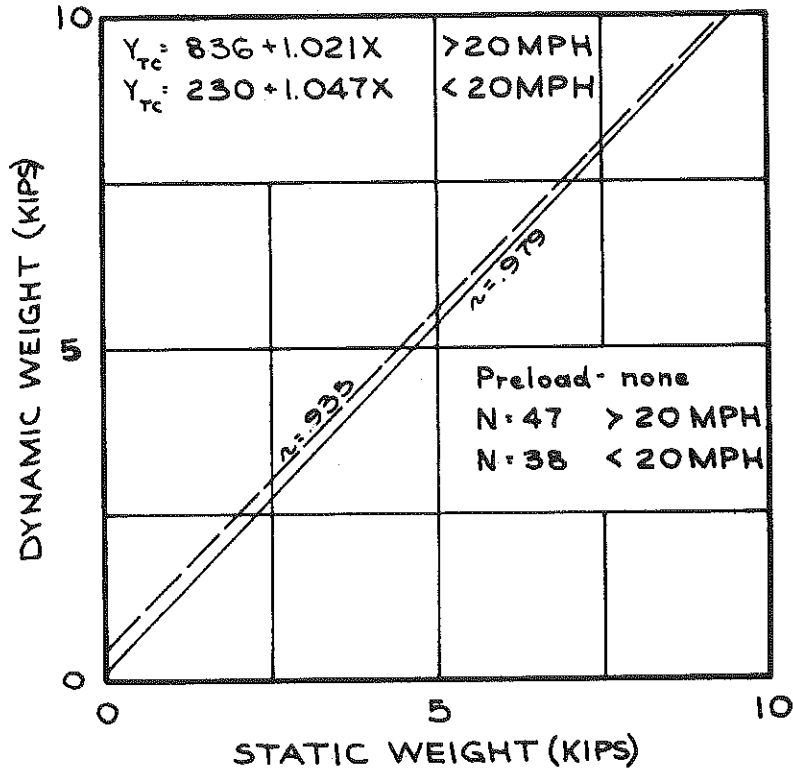


FIGURE 58. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS - FRONT AXLES

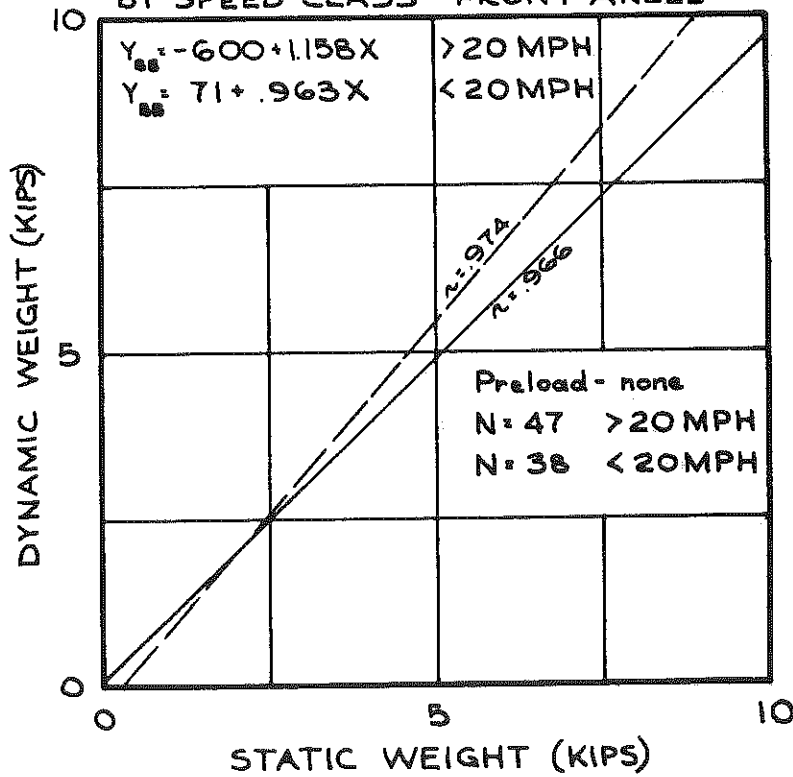
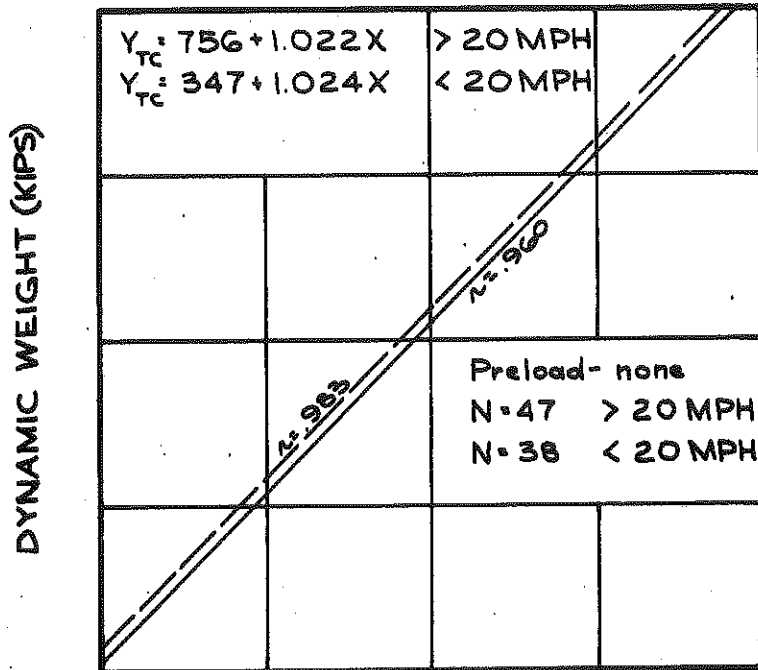
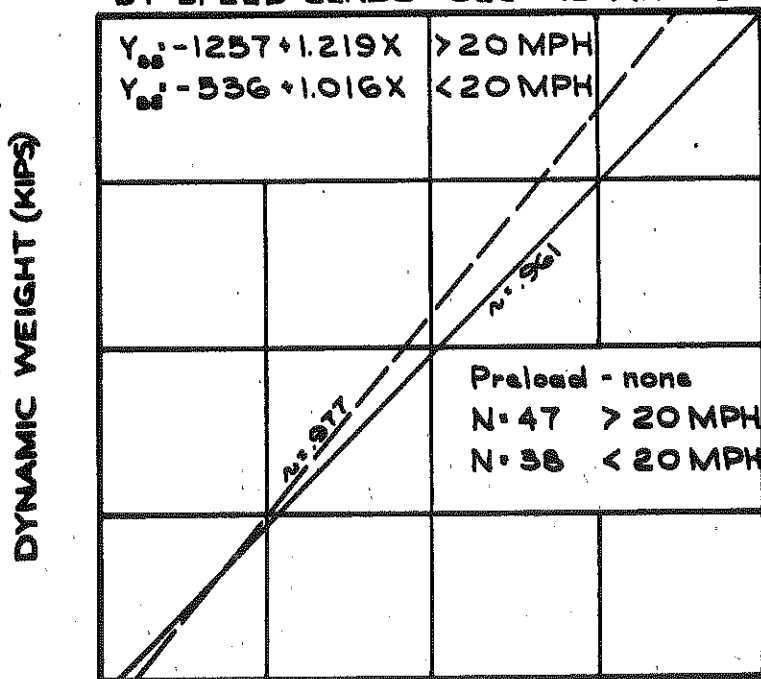


FIGURE 59. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS - FRONT AXLES



STATIC WEIGHT (KIPS)
 FIGURE 60. CORRELATION OF STATIC & DYNAMIC WEIGHTS
 BY SPEED CLASS - SECOND AXLES



STATIC WEIGHT (KIPS)
 FIGURE 61. CORRELATION OF STATIC & DYNAMIC WEIGHTS
 BY SPEED CLASS - SECOND AXLES

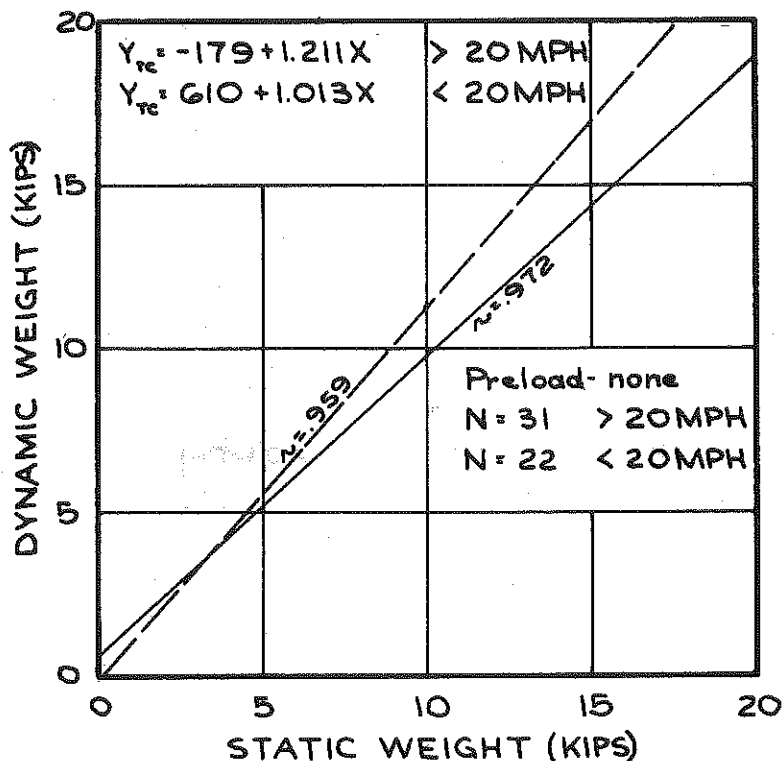


FIGURE 62. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS-THIRD AXLES

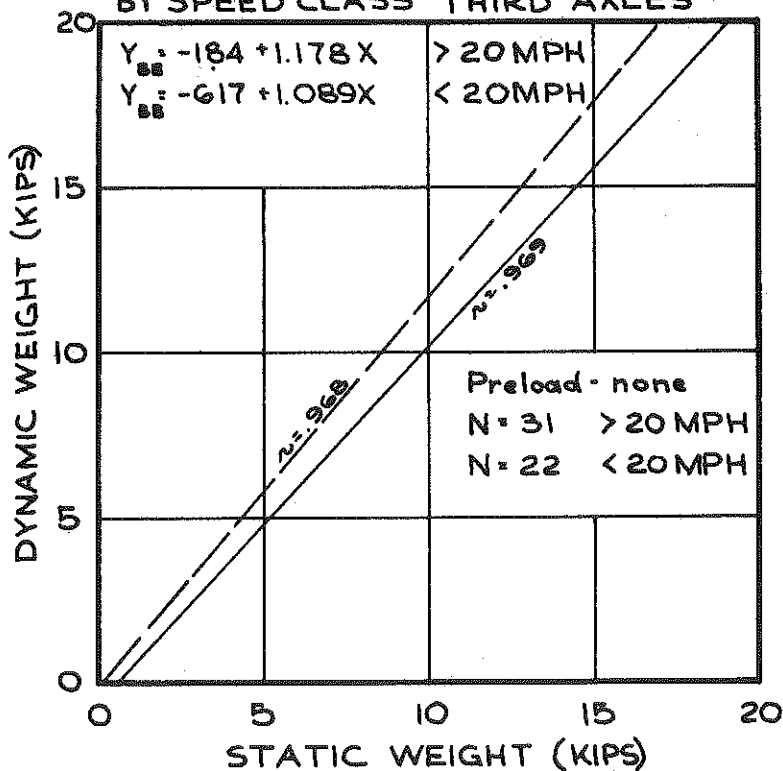
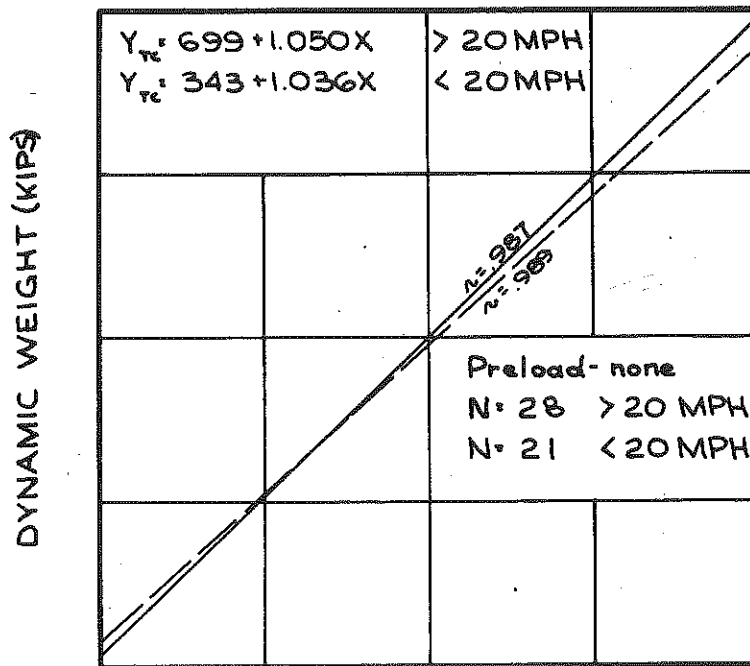
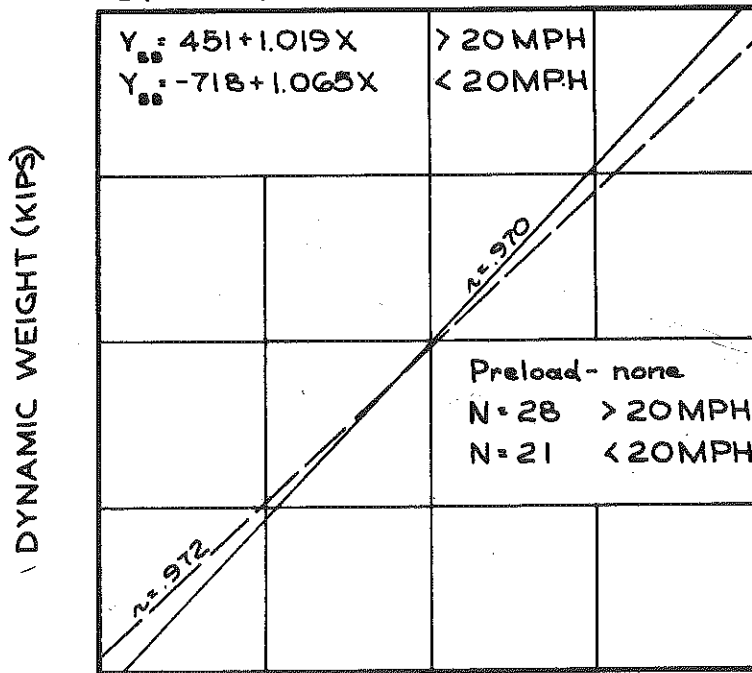


FIGURE 63. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS-THIRD AXLES



STATIC WEIGHT (KIPS)

FIGURE 64. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS-FOURTH & FIFTH AXLES



STATIC WEIGHT (KIPS)

FIGURE 65. CORRELATION OF STATIC & DYNAMIC WEIGHTS BY SPEED CLASS-FOURTH & FIFTH AXLES

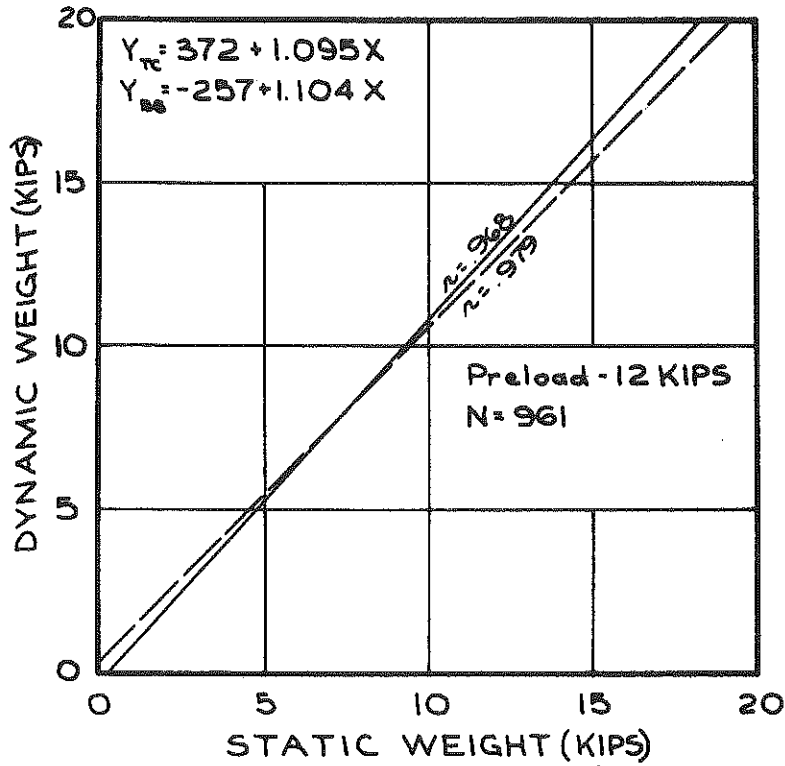


FIGURE 66. CORRELATION OF STATIC & DYNAMIC WEIGHTS,
ALL AXLES

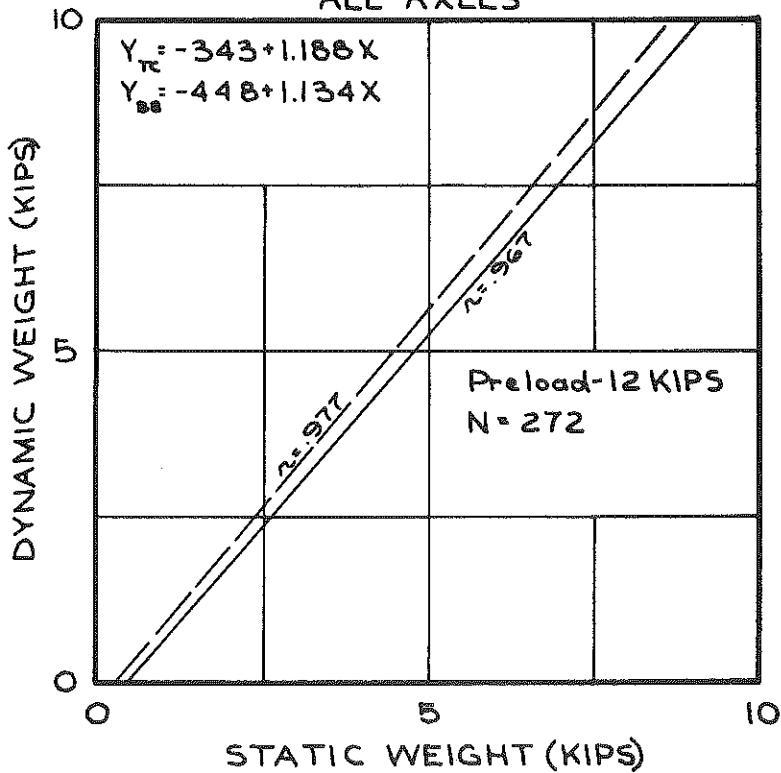


FIGURE 67. CORRELATION OF STATIC & DYNAMIC WEIGHTS,
ALL FRONT AXLES

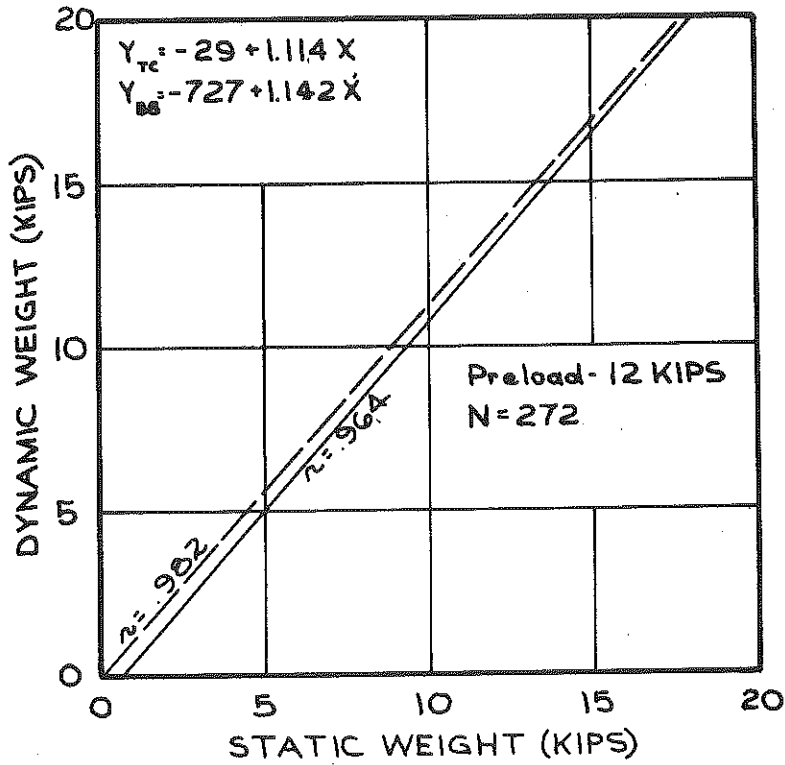


FIGURE 68. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL SECOND AXLES

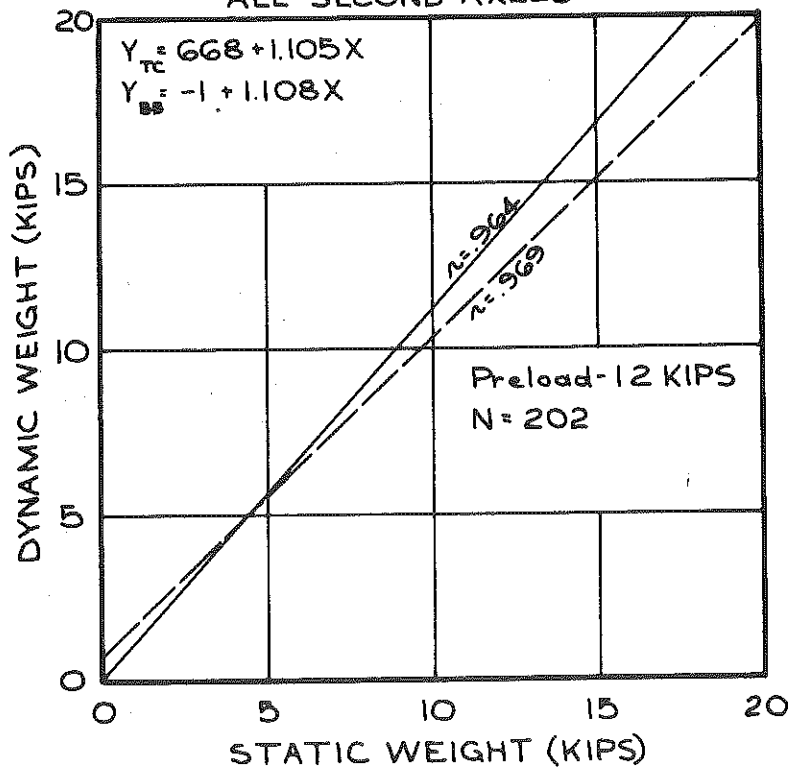


FIGURE 69. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL THIRD AXLES

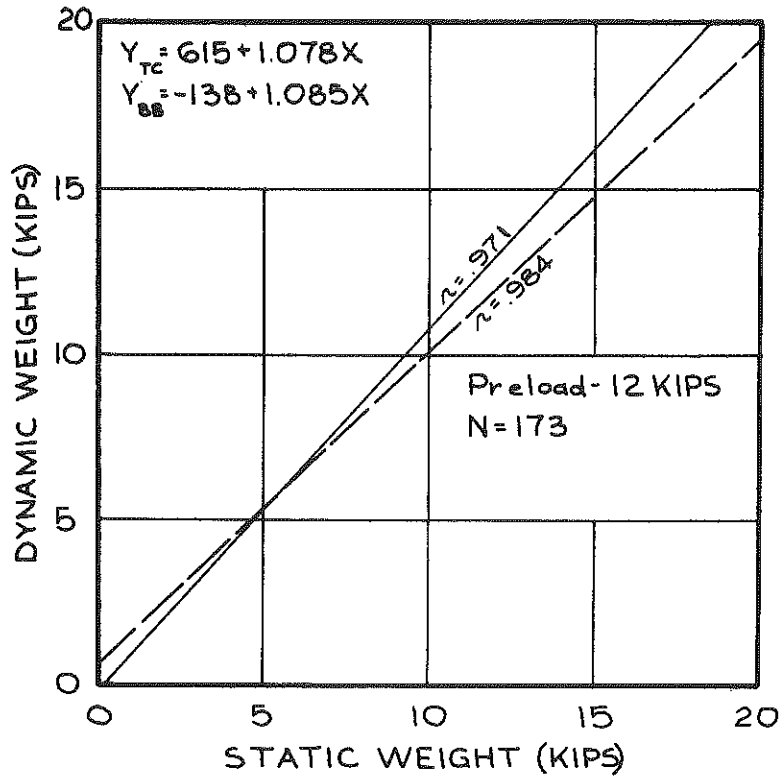


FIGURE 70. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL FOURTH AXLES

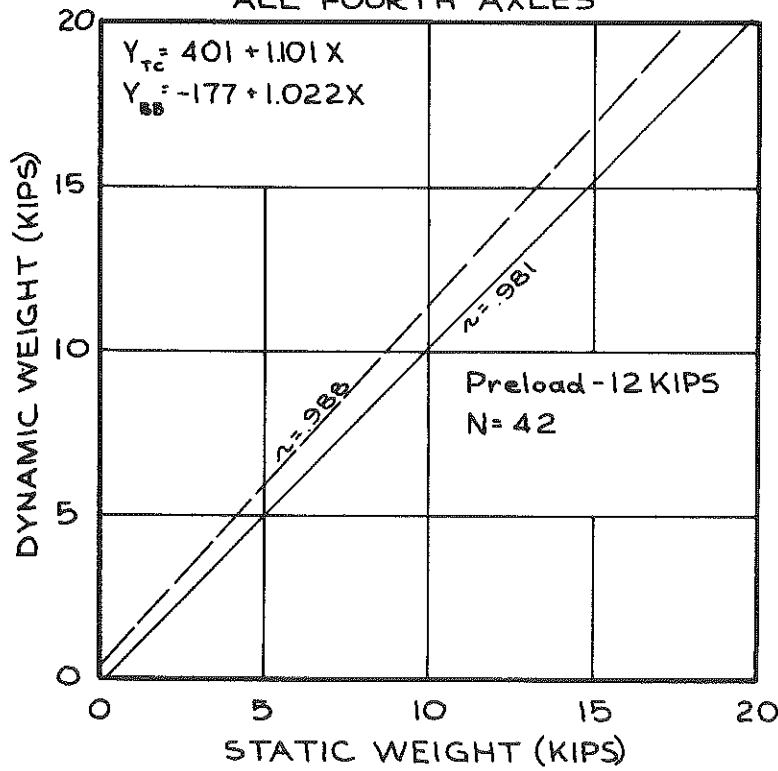


FIGURE 71. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL FIFTH AXLES

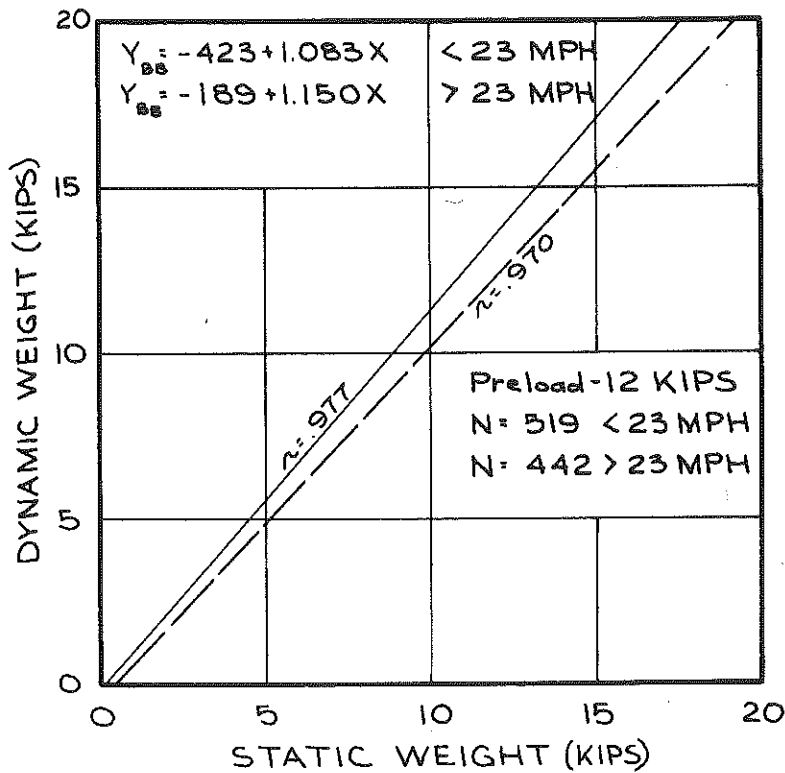


FIGURE 72. CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS - ALL AXLES

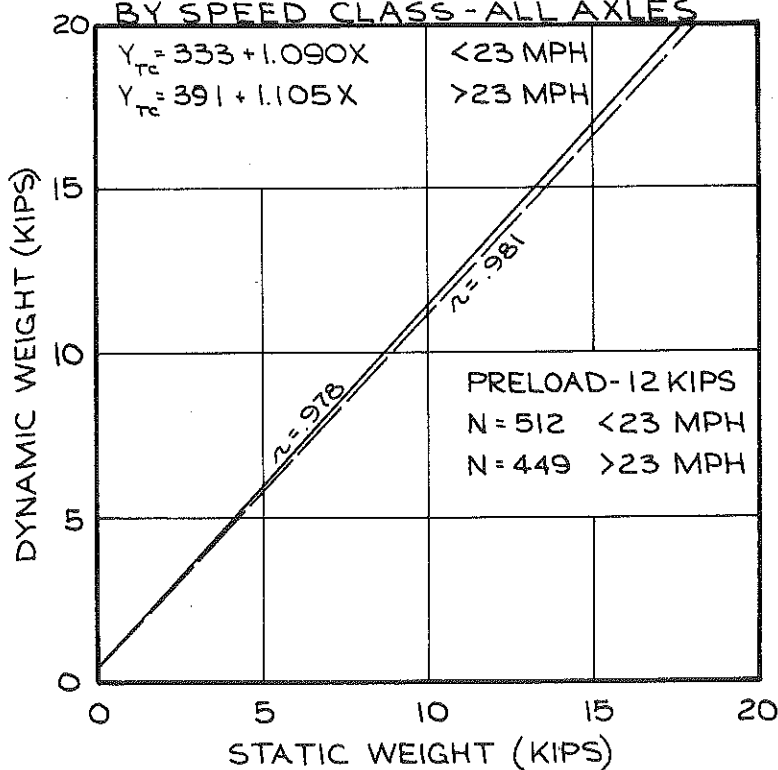


FIGURE 73. - CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS - ALL AXLES

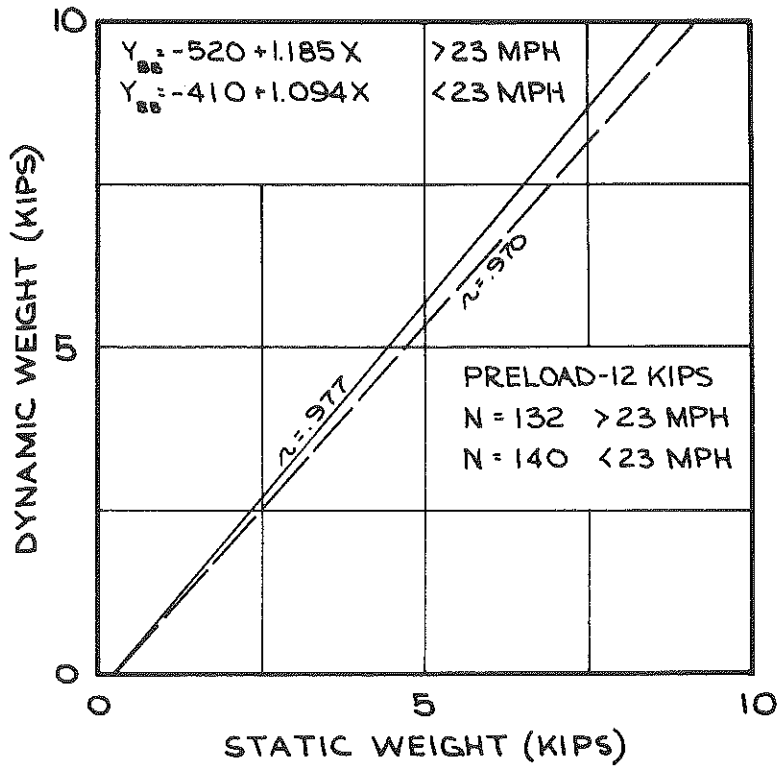


FIGURE 74. CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS-ALL FIRST AXLES

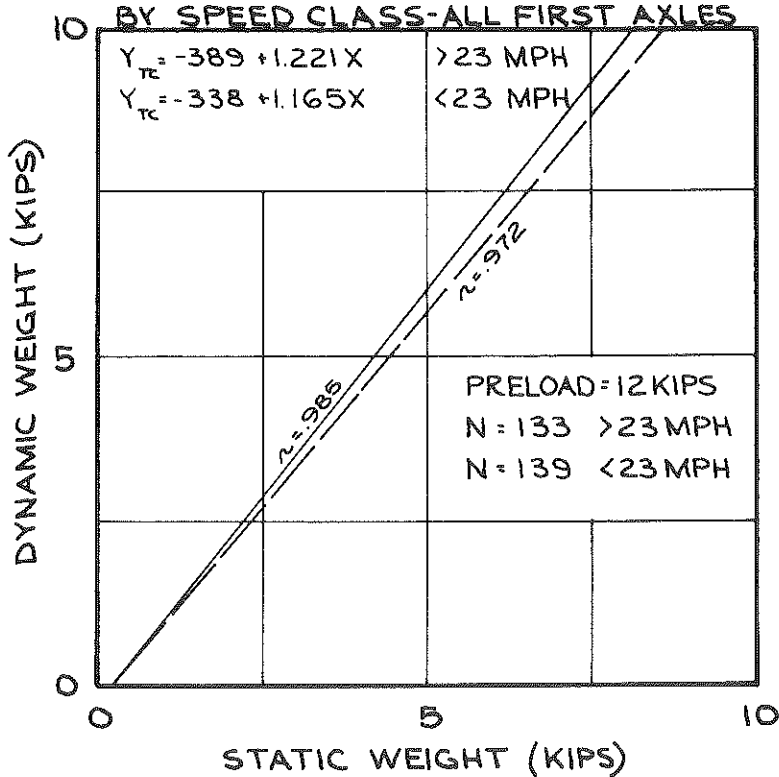


FIGURE 75. CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS-ALL FIRST AXLES

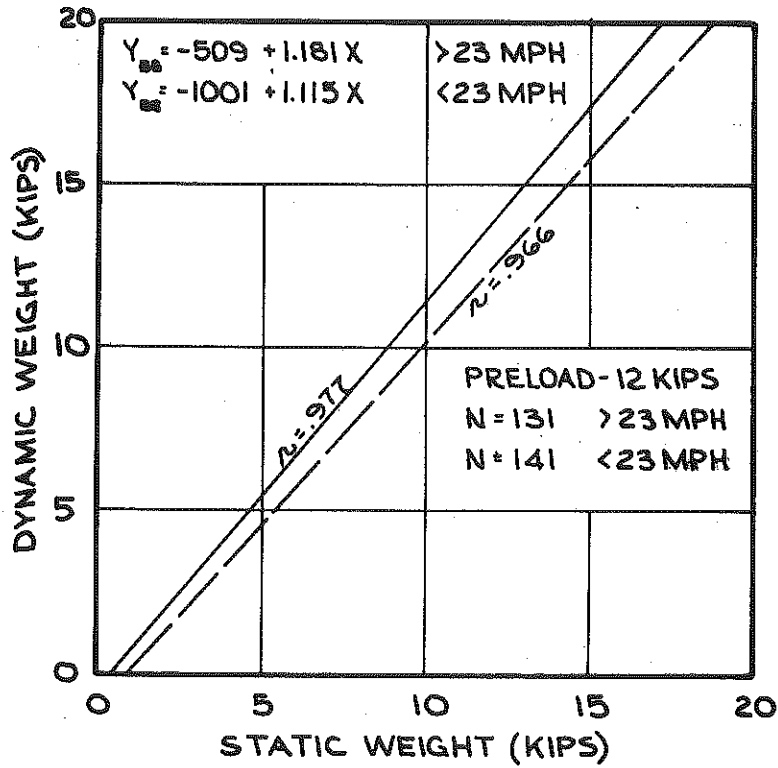


FIGURE 76.-CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS-ALL #2 AXLES

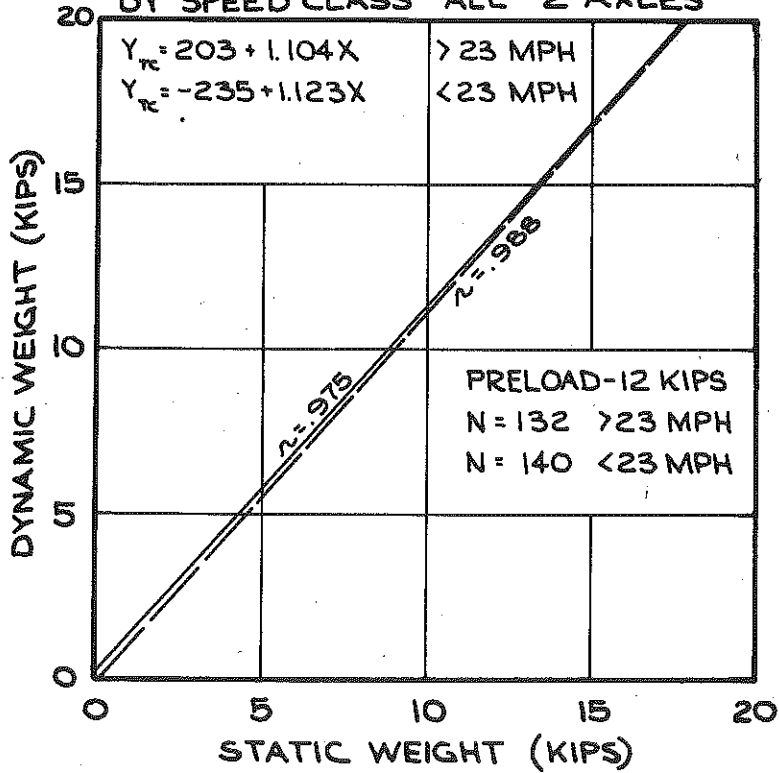


FIGURE 77.-CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS-ALL #2 AXLES

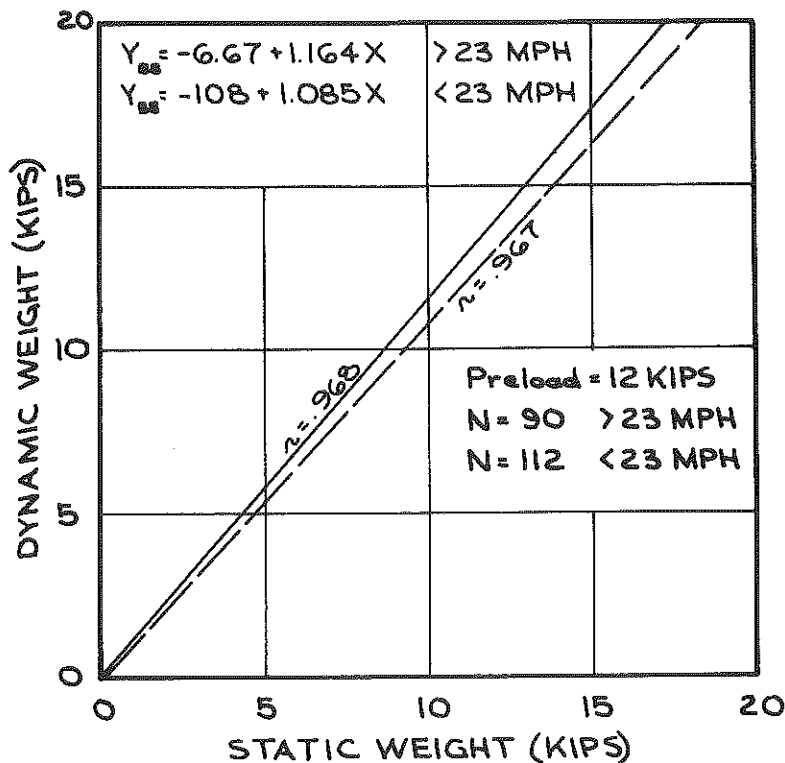


FIGURE 78. CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS-ALL *3 AXLES

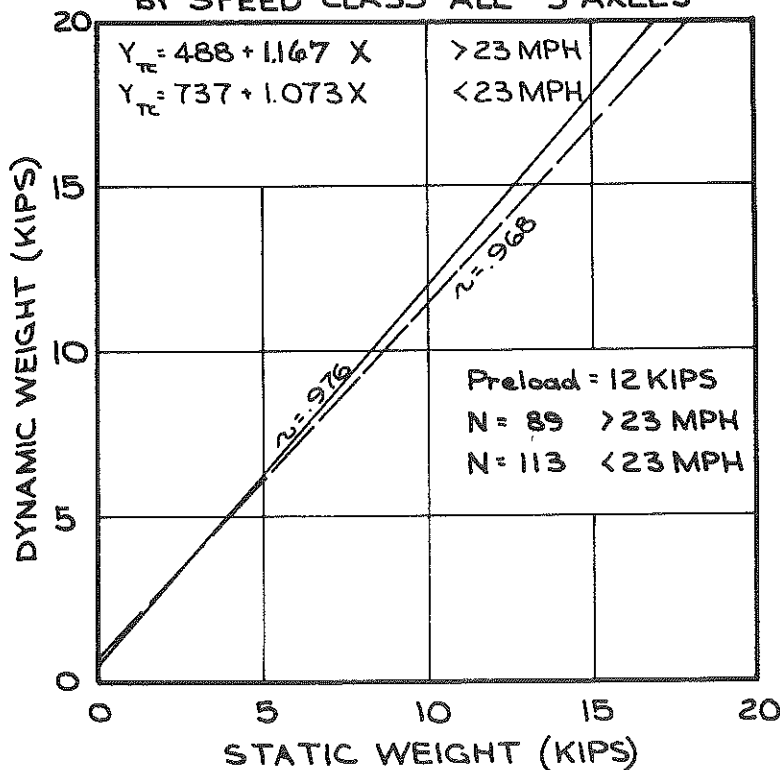


FIGURE 79. CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS-ALL *3 AXLES

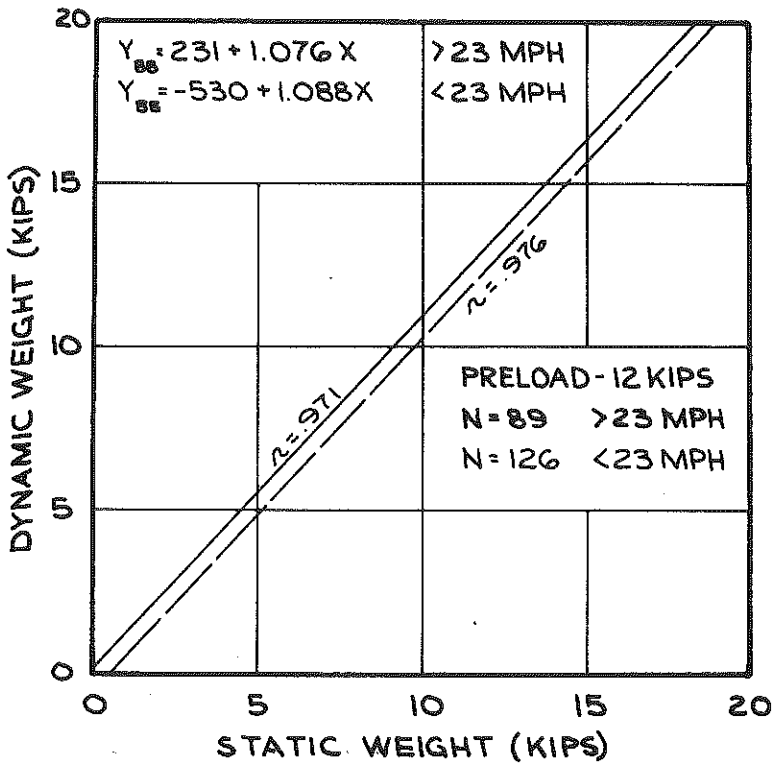


FIGURE 80: CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS - ALL #4 & #5 AXLES

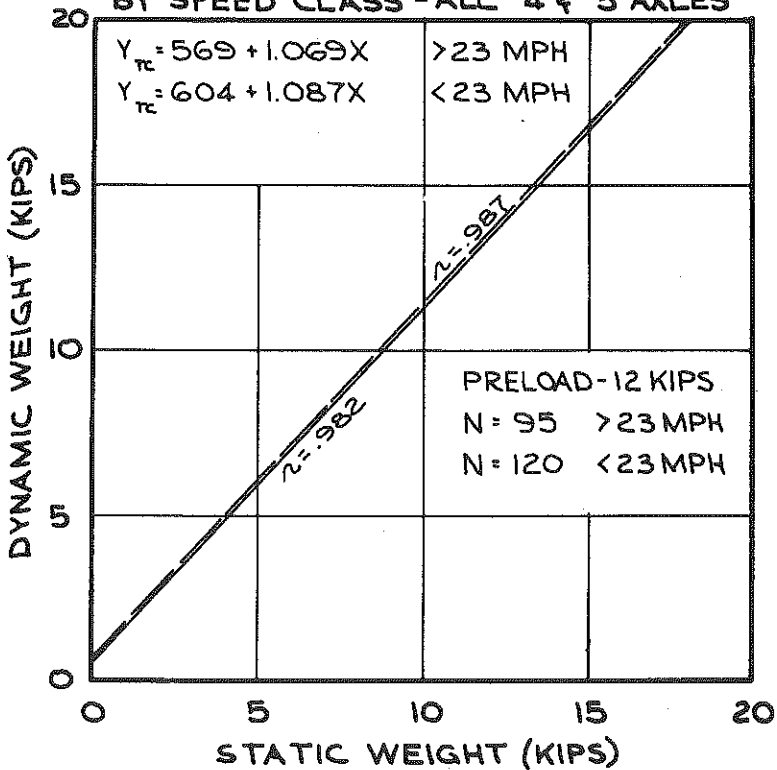


FIGURE 81: CORRELATION OF STATIC & DYNAMIC WEIGHTS, BY SPEED CLASS - ALL #4 & #5 AXLES

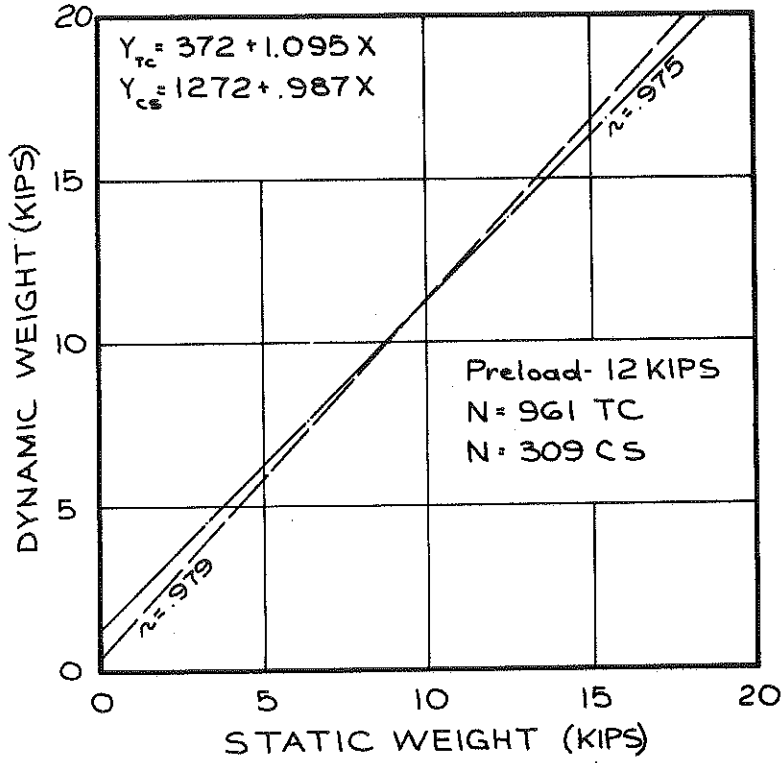


FIGURE 82. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL AXLES

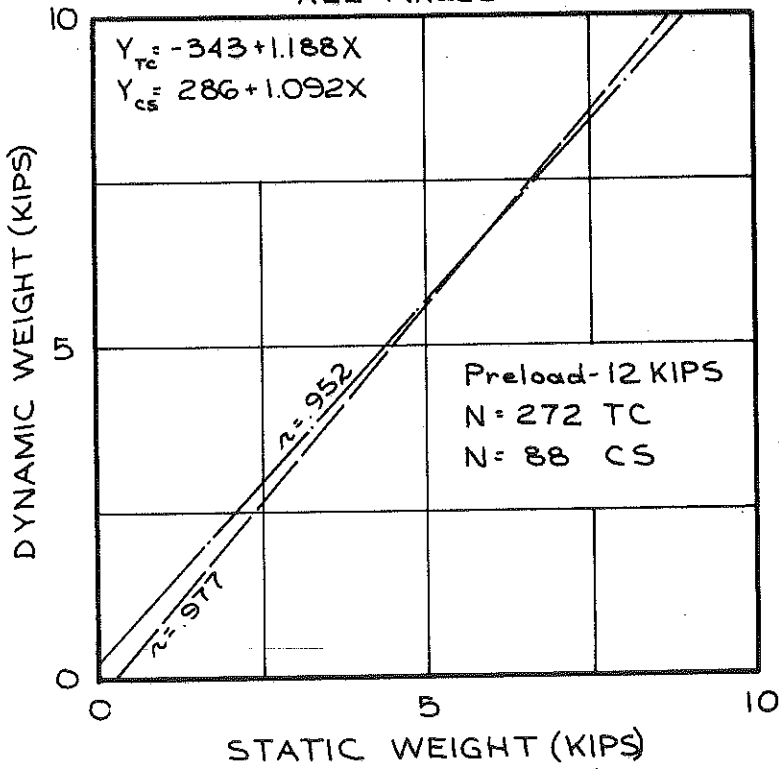


FIGURE 83. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL FRONT AXLES

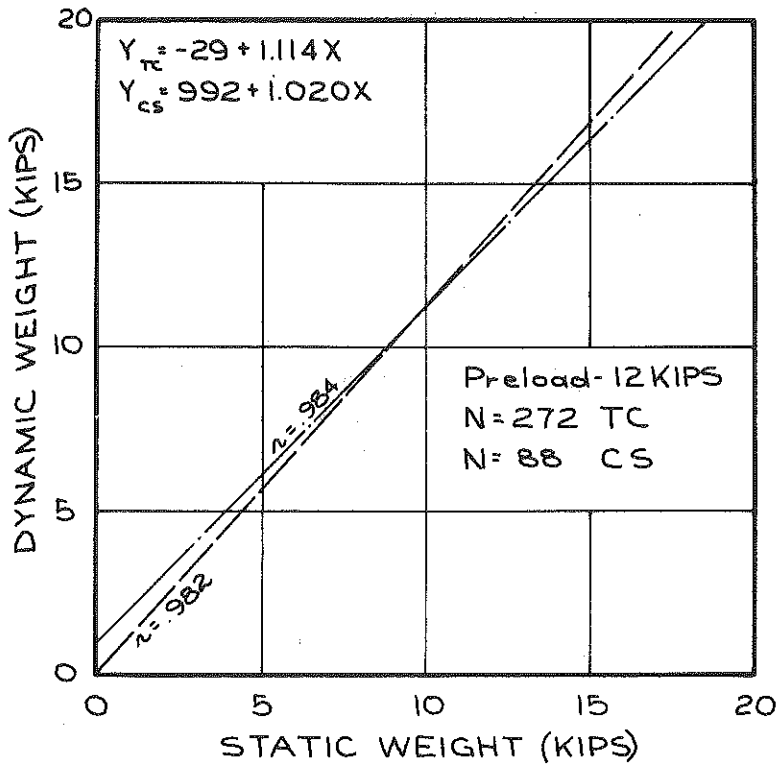


FIGURE 84. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL SECOND AXLES

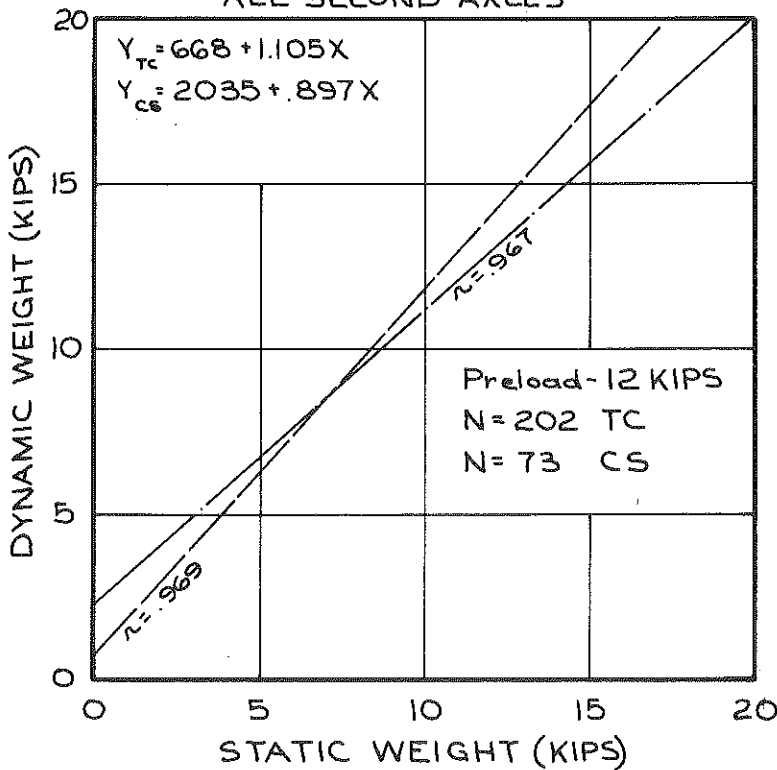


FIGURE 85. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL THIRD AXLES

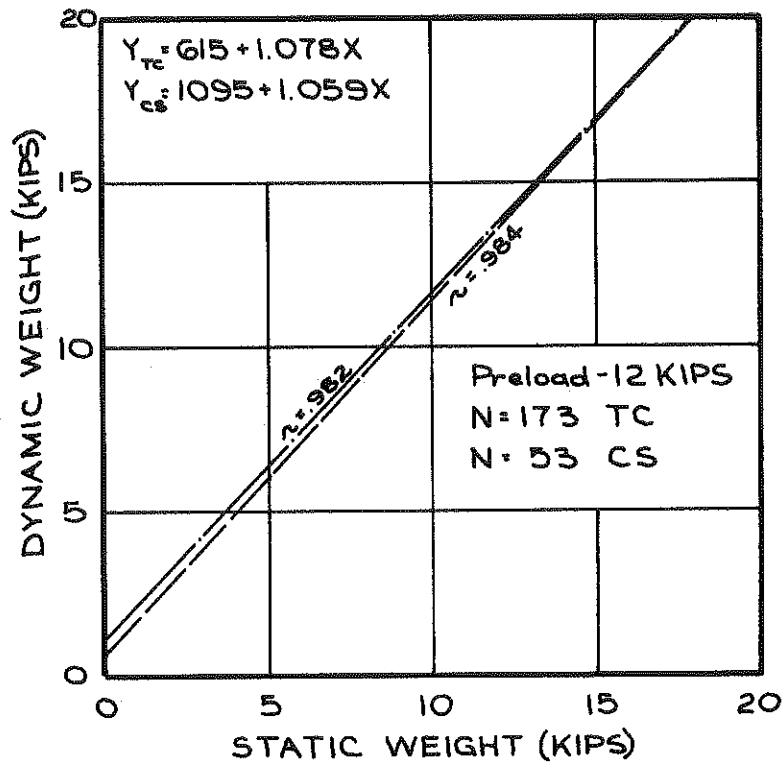
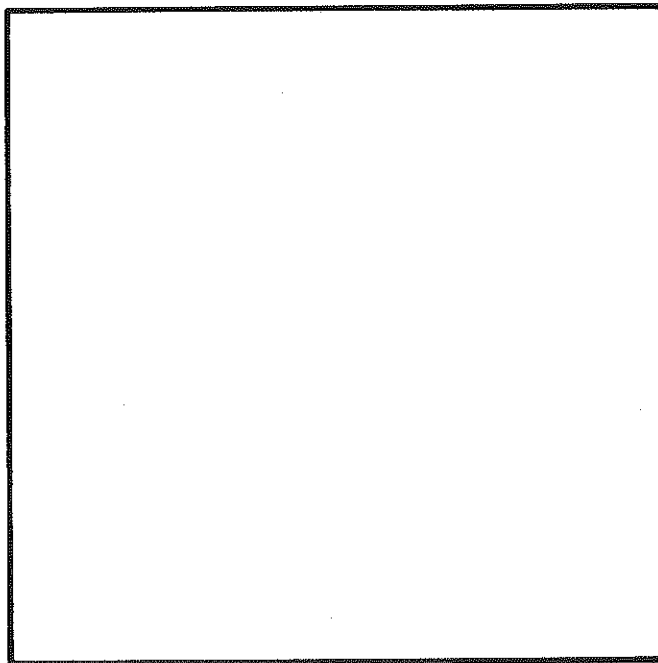


FIGURE 86. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL FOURTH AXLES



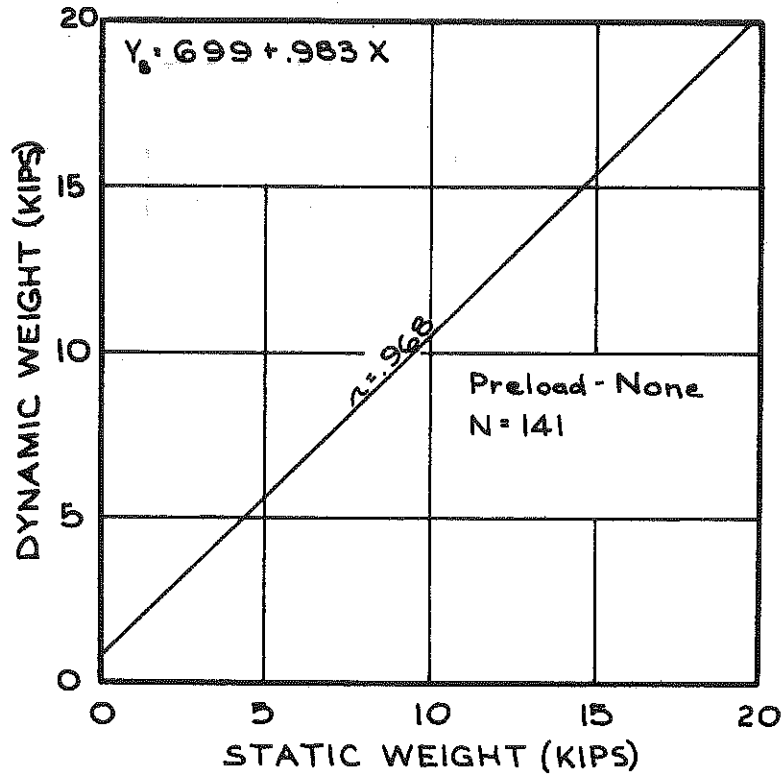


FIGURE 87. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL AXLES

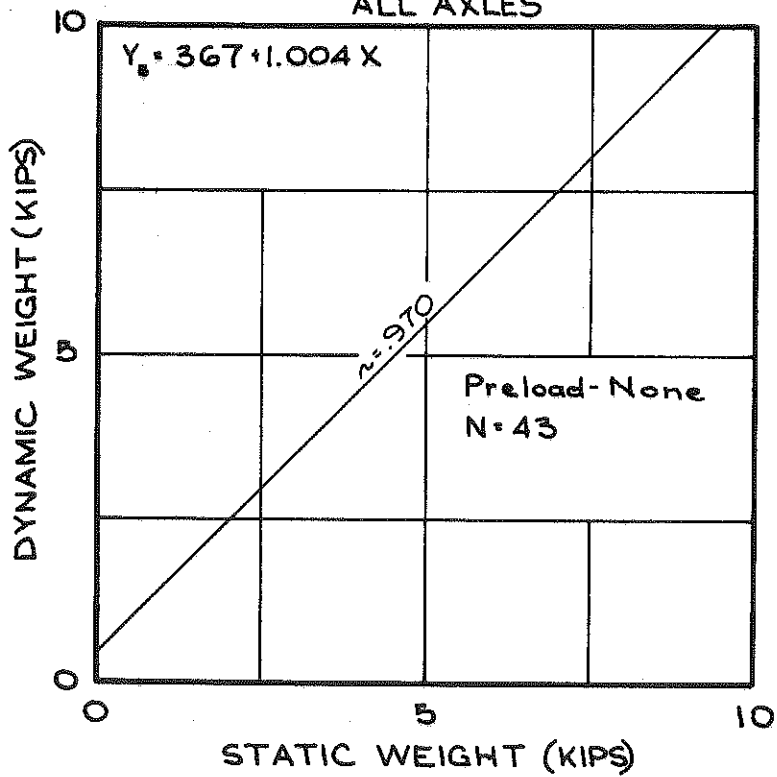


FIGURE 88. CORRELATION OF STATIC & DYNAMIC WEIGHTS ALL FRONT AXLES

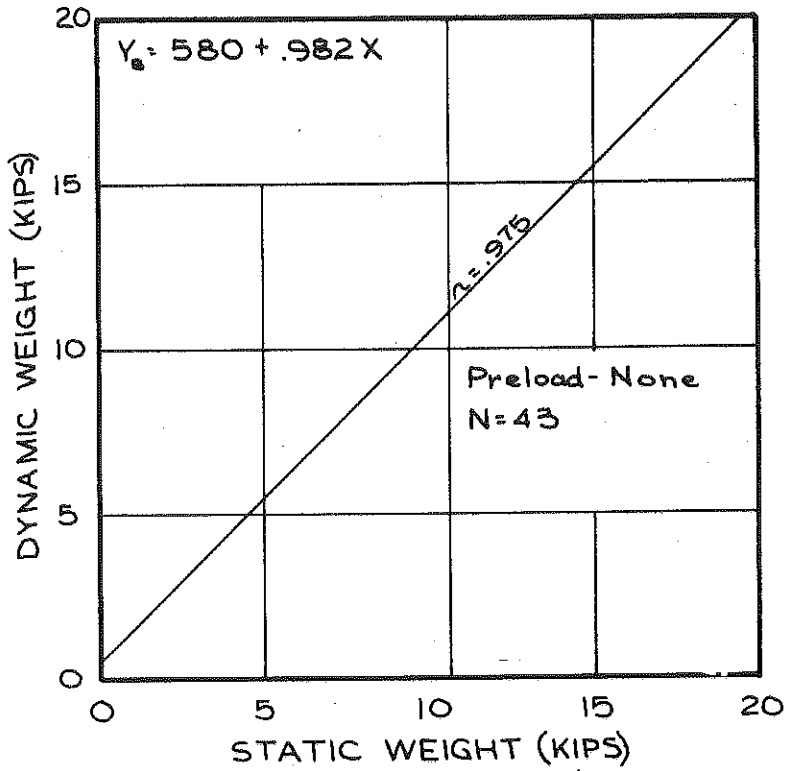


FIGURE 89. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL SECOND AXLES

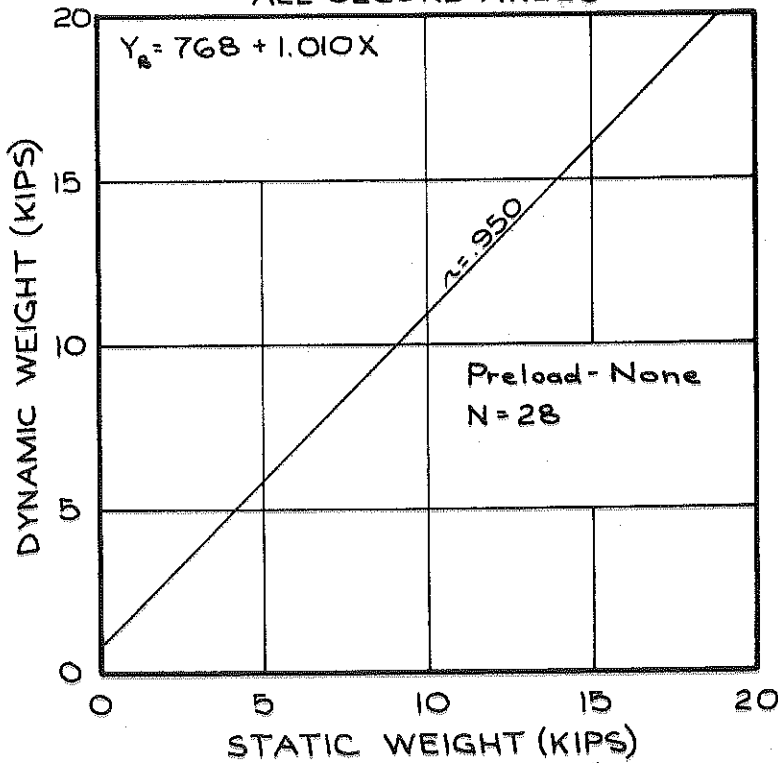


FIGURE 90. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL THIRD AXLES

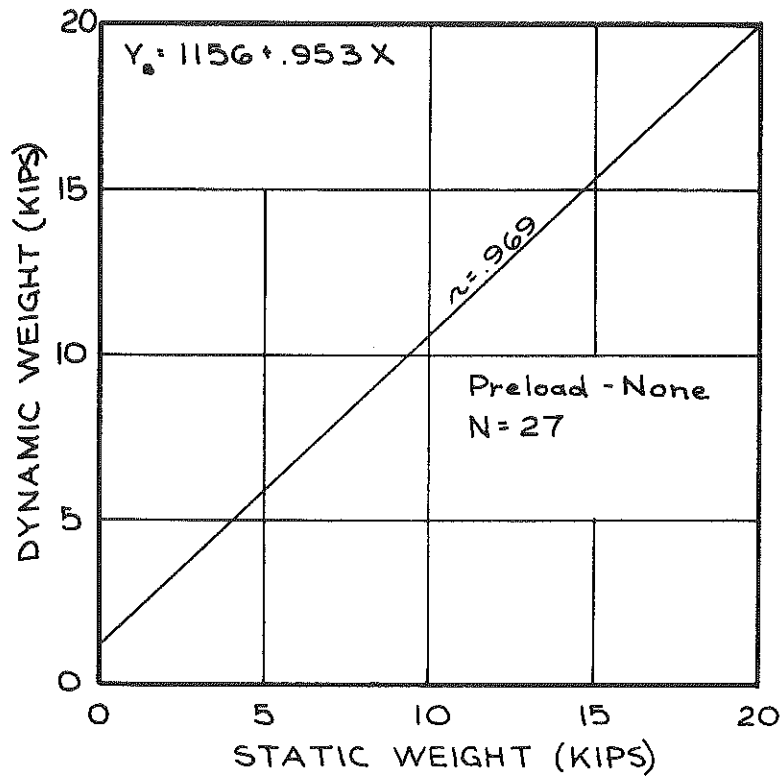
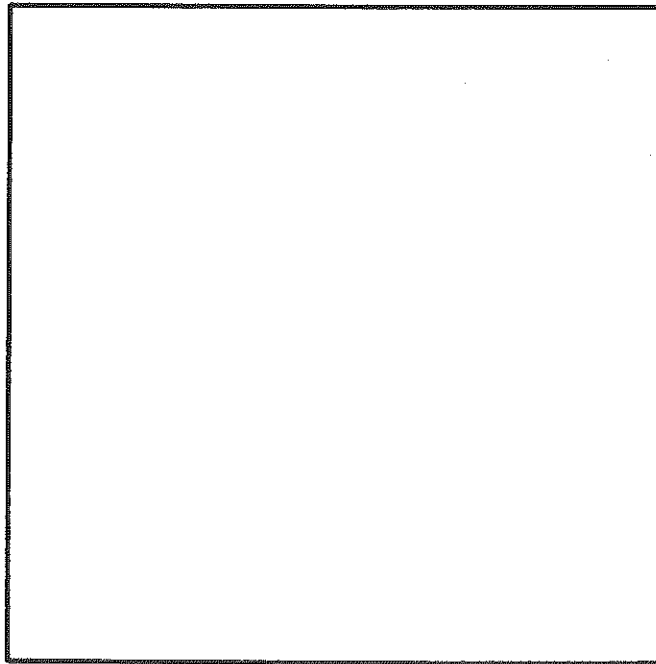


FIGURE 91. CORRELATION OF STATIC & DYNAMIC WEIGHTS, ALL FOURTH & FIFTH AXLES



CHAPTER V

CONCLUSIONS AND RECOMMENDATIONS

The conclusions that may be reached from the preceding analyses depend upon the specific function which the weighing system is expected to perform and the ultimate use of the weight data collected.

In light of present-day highway and traffic engineering technology there are at least five basic areas in which the weighing of vehicles in motion could play an important role. These are:

(1) Highway planning and economics - A better knowledge of the number and frequency of axle loads in the various weight groups that might be expected to occur on a proposed highway would facilitate planning decisions as to construction and future maintenance costs and the incremental sharing of these costs through road user taxes.

(2) Design of the roadway structure - Practically all of the existing procedures for determining pravegment thickness require that an estimate be made of the number of daily or yearly applications of an "equivalent wheel load." The collection and analysis of large samples of dynamic axle load data on all classes of roads would serve to improve present methods of computing the EWL's and could lead to the development of better design procedures.

(3) Research - Much remains to be learned about the action and reaction between a moving vehicle and the pavement over which it rolls. The selection of the proper impact factor to use in the design of highway bridges is still primarily a matter of guess work. The effect of repeated dynamic load applications upon road subgrades is of abiding interest to the highway engineer.

Research into all of these problems would require a large amount of historical axle load data. A dynamic scale, properly placed and instrumented could be used to collect such information.

(4) The collection of axle load data for statistical purposes - This work is now done by statically weighing a very small sample of truck axles at a high unit cost in time and money.

(5) Law enforcement - The detection of overweight axles now requires that nearly every truck be stopped and statically weighed, axle by axle. A simple electronic scale could be pre-set to signal the passage of only those axles which, within the "accuracy" limits of the scale, appeared to be illegally loaded.

In the first three areas of application the weight values needed are actually the dynamic forces applied to the road surface by the tires of the moving vehicle. It is believed that the determination of these forces at a specific location along a highway is the primary function of the dynamic scale and the one for which it is best suited. It is also believed possible however to obtain, with the dynamic scale, a fair approximation of static axle weights through the use of appropriate electronic equipment. It was then, in consideration of each of these functions that the following conclusions were reached.

Conclusions

The Taller-Cooper Scale

This scale was designed to measure loads applied by the axles of a slowly moving vehicle. Its response to fast moving loads can be improved by heavy pre-loading. A resilient preloading device such as the coil spring is better than the rod and turnbuckle for this purpose.

The output wave form of the Taller-Cooper scale lends itself to automatic measurement and recording of the loads applied to it. Since

the platform is about three feet wide a vehicle having a high frequency of variation in weight, and moving at a slow speed across the platform will cause the scale to yield a rapidly varying output. Electronic sampling and averaging of the wave form variations to obtain a closer approximation of static weight is entirely feasible. There is, of course, no assurance that an averaged occurrence of the static weight will take place during the time the axle is on the platform, but at relatively slow speeds the accomplishment of a full cycle of the vehicle's periodic undulation is more likely than at higher speeds.

To summarize; use of the Teller-Cooper scale is indicated when the measurements are to be made and recorded without further manipulation of the recorded weights, as in automatic data collection systems.

The Broken Bridge Scale

The Broken Bridge, because it yields a single, discrete measurement of a load applied to it is not well suited for the automatic recording and averaging of dynamic weight measurements.

Its single peaked output wave form represents the dynamic load applied to the scale at one distinct point in time - the instant that the axle passes over the junction between the two halves of the platform. This time interval is far too short to permit a sampling of the vehicle's weight oscillations to take place. The Broken Bridge scale therefore is better adapted to the measurement of point weight values and the classification of the applied loads into weight groups.

Stabilization of the Broken Bridge platform by preloading with coil springs results in a smoother output wave form and some improvement in the consistency of the dynamic weight measurements.

The Beam Type Scale

The experimental beam scale, though not tested as extensively as the other two, appears to be a practical device for the measurement of dynamic loads. Averaging the two peaks of its characteristic output waveform yields values which in some instances more closely approximate static axle weights than similar weighings with the Taller-Cooper and Broken Bridge scales.

The principal use of the beam type scale is in the continuous collection of axle load data from the normal traffic stream. An inexpensive, lightweight version of this scale with the necessary portable recording equipment would be useful in any application requiring large samples of load history data at scattered locations throughout the highway system.

Recommendations

The Dynamic Scales

(1) The Taller-Cooper scale is recommended for use in applications 3, 4, and 5 above.

(2) The Broken Bridge scale is recommended for use in applications 1, 2, 4, and 5.

(3) Pending further study of its performance and the advisability of making certain design modifications, the beam type scale is recommended for use in applications 1, 2, 4, and 5.

Future Research

Further research effort in the field of dynamic weighing should include:

(1) The development of a portable scale designed to be installed in the pavement at previously prepared locations in the state and federal

highway systems where the axle load characteristics of the traffic are desired. These dynamic weighing stations should be located adjacent to the Automatic Traffic Recorder (ATR) sites where possible.

(2) A feasibility study of the use of the dynamic scale to measure speed, volume and axle spacing in addition to axle weight.

(3) The installation of either the Taller-Cooper or Broken Bridge scale in the approach to an enforcement weighing installation to test the practicality and desirability of culling out lightly loaded trucks from those required to stop for static weighing.

(4) A study of a very large sample of dynamic weight recordings to determine the feasibility of deriving approximate static weights by a statistical consideration of the effects of specific approach conditions, crossing speeds, axle location, scale type and preload.

To summarize the findings of this project thus far:

(1) Any of the three scales tested will accurately measure the applied load. (See Appendix D).

(2) Each of the three scales will perform satisfactorily in the applications for which it is peculiarly suited.

(3) The most important use of the dynamic scale is in the measurement of forces applied to the highway surface by the axles of a moving vehicle.

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11. [unclear]

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APPENDIX X

A COMPREHENSIVE BIBLIOGRAPHY
WITH SYNOPSES OF SELECTED ENTRIES

QUESTION

1. A company has a net income of \$100,000.

2. The company has 100,000 shares of common stock.

WEIGHING VEHICLES IN MOTION

A Comprehensive Bibliography with Synopses of Selected Entries

Preface

Since 1960 a research¹ team at the University of Kentucky's College of Engineering has been studying the problem of weighing moving vehicles. The research, jointly sponsored by the Kentucky Department of Highways and the Bureau of Public Roads, has as its primary purpose the development of a dynamic weighing platform that will best perform the axle weighing function in an automated traffic data collection system.

The first phase of the work was an attempt to locate and study all extant literature pertinent to the subject of dynamic weighing. The results of this initial search were summarized in two articles compiled by members of the research team. (14, 15)² Since these articles were published (in 1961) there have been many notable advances in the field, both in the United States and overseas. The following bibliography and selected synopses are intended to supplement the previous work and to provide interested persons with an overall background on which further research might be based.

The listings are subdivided according to the various aspects of the problems as they have been encountered by the Kentucky team and by others working in the same area. The bibliography refers to a number of letters, memoranda and construction plans now in the project files at the University of Kentucky. This material is available to interested individuals or groups upon approval of the sponsoring agencies. Also included is a list of selected reference works on the mechanics and electronics involved in dynamic weighing.

Synopses of certain articles thought to be particularly relevant to the theory and development of dynamic weighing are arranged numerically at the end of the bibliography. Following the synopses is a brief summary of the most recent developments in the field as obtained from reports of the Kentucky and Michigan projects and from recent correspondence with other researchers in the United States and Europe.

¹Principal Members of the research team are: David K. Blythe, Civil Engineering Department Head, project director; John A. Dearing, Associate Professor of Civil Engineering, assistant project director; Russell E. Puckett, Assistant Professor of Electrical Engineering, instrumentations engineer.

²Numbers refer to items listed in the Bibliography.

B I B L I O G R A P H Y

General

COLLECTION AND USES OF TRUCK WEIGHT DATA

1. Truck Weighing. "Fleet Owner." (A special report by the Editors)
Government Printing Office, Washington, D.C.
2. Report of the Testing of Vehicle Scales by Bureau of Standards in
Cooperation with the States. NATIONAL BUREAU OF STANDARDS.
Miscellaneous Publication #195.
3. Developments in Electronic Weighing. NATIONAL BUREAU OF STANDARDS.
Miscellaneous Publication #199. May 1950.
4. Electronic Weighing. "Scale Journal." November 1952. p. 5.
5. Electronic Weighing. "Scale Journal." March 1955. p. 4.
6. Developments in Weighing. "Instrument and Control Systems." Vol. 33,
July 1960. p. 1144.
7. Some Statistical Evaluations of Truck Weight Characteristics in
Mississippi. BORIS B. PETROFF and J. H. SUMNERS. Highway Research
Board Bulletin #303, 1961. pp. 48-61.
8. Use of Loadometer Data in Designing Pavements for Mixed Traffic. JAMES
F. SHOOK, L. J. PAINTER, and T. Y. LEPP. Presented at Annual
Meeting of Highway Research Board, Washington, D.C. January 1963.

See also: 46, 47.

*DYNAMIC WEIGHING

- *9. Weighing Vehicles Static and In Motion by Electronic Scales. O. K.
NORMANN. SAE Transactions. Vol. 63. 1955. p. 373.
10. Weighing Vehicles in Motion. HEATLEY, J. J. AASHO Convention, Papers
and Discussions. 1956. pp. 70-71.
11. Electronic Weighing. O. K. NORMANN. AASHO Convention, Papers and
Discussions. 1956. pp. 140-149.
- *12. Truck Motion Weighing Report T-38. J. J. HEATLEY CO. Smithtown,
N. Y. 1956.
13. Weighing Trucks on the Move. M. ROUSSE. "Monthly Bulletin of the
International Railway Congress Association" (English Edition).
November 1959. pp. 1083-1089.
14. Dynamic Weighing of Vehicles. J. A. DEARINGER. "Public Roads."
October 1961. pp. 200-210.

*Indicates that a synopsis of this article appears at end of bibliography.

15. A Survey of Components and Systems for Measuring Dynamic Loads. R. E. PUCKETT and S. E. KNIGHT. Engineering Experiment Station Bulletin. Vol. 16, No. 2 University of Kentucky. December 1961.

THE LOAD CELL SCALE

- *16. Weighing Vehicles in Motion. O. K. NORMANN and R. C. HOPKINS. Highway Research Board Bulletin #50. 1952.
- *17. An Apparatus for Measuring, Classifying and Counting the Wheel Loads of Moving Vehicles. J. J. TROTT and P. J. WILLIAMSON. Department of Scientific and Industrial Research, Road Research Laboratory (Great Britain). Research Note No. RN 34871JJT.PJW. May 1959.
- See also: 14, 45.
- *18. Die Automatische Achslastwaage bei Grunbach (Remstal). W. SCHWADERER and W. REIMUND. "Strasse Und Autobahn." 1959. pp. 41-47.
19. Annual Report on Research Project, Weighing Vehicles in Motion. KENTUCKY RESEARCH FOUNDATION. University of Kentucky. Lexington, Kentucky, 1961.
20. A Description and Analysis of the Broken Bridge Type Electronic Scale. C. C. SCHIMPELER. Unpublished Thesis. Master of Science in Civil Engineering. University of Kentucky. 1962.

OTHER TYPES OF DYNAMIC SCALES

21. Mississippi Engineer's Design Scales for Weighing Trucks. BYRD MALLEY. "Mississippi Highways." February 1956, p. 10.
22. A Portable Electronic Scale for Weighing Vehicles in Motion. EDWARD C. LEE. Unpublished Thesis, Master of Science in Civil Engineering. Mississippi State College. May 1956.

See also: 14

THE BEAM TYPE SCALE

- *23. Weighing Vehicles in Motion. S. P. MAGGARD. Unpublished Thesis. Master of Science in Civil Engineering. University of Kentucky. 1957.
24. Axeltrycksmatningar (Axle load Measurements). STIG EDHOLM. Statens Vajenstitut, Rapport 35. 1960

See also: 19

Field Installations

KENTUCKY

25. Annual Report on Research Project, Weighing Vehicles in Motion. KENTUCKY RESEARCH FOUNDATION, University of Kentucky. Lexington, Kentucky. 1962.

ILLINOIS

26. Construction Plans and Specifications, Electronic Scale for AASHO Test Facility. ILLINOIS DIVISION OF HIGHWAYS. (In Project Files, KRF 3359).
27. Inspection of Electronic Scale, AASHO Test Facility. R. E. PUCKETT. University of Kentucky. Letter report to D. K. Blythe. June 13, 1960. (In Project File, KRF 3359)

INDIANA

28. Electronic Scale Used on Indiana Turnpike for Weighing Trucks in Motion. HIGHWAY RESEARCH ABSTRACTS. Vol. 26, No. 7. July 1956. p. 8.

IOWA

- *29. Weighing Trucks in Motion. (A Report) IOWA STATE HIGHWAY COMMISSION. October 1954.
- *30. Iowa Research Scales Go Electronic. J. J. HEATLEY. "Traffic Engineering." December 1957. p. 18-19, 50.
31. Letters of May 25 and June 8, 1960 to D. K. Blythe. IOWA STATE HIGHWAY COMMISSION. (In Project Files, KRF 3359).
32. Inspection trip to Iowa Installation. R. E. PUCKETT. Letter report to D. K. Blythe. University of Kentucky. July 20, 1960. (In Project Files, KRF 3359).

MICHIGAN

33. Memorandum to Research Team, Inspection of Electronic Scale at Michigan State Highway Department Research Lab. D. K. BLYTHE, July 12, 1960 (In Project Files KRF 3359 - Concerns experimental installation of MSHD at Fowlerville, Mich.)
34. Progress Report on Part A, Phases II & III, Michigan Project 52 F-26. EPSCO INCORPORATED, Cambridge, Massachusetts. October 1961.

See also: 74

MINNESOTA

35. Construction Plans for Weighing Station. MINNESOTA DEPARTMENT OF HIGHWAYS. July 1954. (In Project Files, KRF 3359.)
- *36. Electronic Weighing Equipment. STATE OF MINNESOTA, DEPARTMENT OF HIGHWAYS. (Report). November 1956.

OREGON

- *37. Weighing Trucks in Motion and the Use of Electronic Scales for Research. W. W. STIFFLER and R. C. BLENSLY. Oregon State Highway Department. November 1955.

38. History of Repairs and Calibrations of the Electronic Scales. Baldock Freeway Test Section, OREGON STATE HIGHWAY DEPARTMENT. November 1956 to December 1957.
39. Letter to J. A. Dearing, University of Kentucky. F. B. CRANDALL. Oregon State Highway Department. November 4, 1959. (In Project Files, KRF 3359).

VIRGINIA

40. Construction Plans for Electronic Scale. VIRGINIA DEPARTMENT OF HIGHWAYS. Woodbridge, Virginia. (In Project Files, KRF 3359).
41. The Oscilloscope Had an Eye on You. "Virginia Trucks." Vol. 23. March 1955. p. 5.
42. New Electronic Scale that Weighs Truck in Motion is Getting a Try in Virginia. "Fleet Owner." Vol. 50, August 1955. p. 35.
43. Letter to D. K. Blythe. K. M. WILKINSON. Virginia Department of Highways. May 26, 1960. (In Project Files, KRF 3359).

GERMANY

44. Weighing Moving Motor Vehicles. WOLFGANG BACHMAN. "Trends, German Construction Engineering." (Otto Elsner Verlagsgesellschaft, Schofferstrasse 15, Darmstadt). No. 12. June 30, 1959. pp. 870-871.

See also: 18

GREAT BRITAIN

45. Composition of Traffic as Found by the Automatic Weigh Bridge on the Pavement Design Experiment on A. 1 at Alconbury Hill, Huntingdonshire. P. J. WILLIAMSON. Department of Scientific and Industrial Research, Road Research Laboratory Research Note No. RN/3488/PJW. May 1959.

See also: 17

SWEDEN

- *46. Methods of Traffic Measurement - Determination of Number and Weight of Vehicles. S. EDHOLM. Highway Research Board Bulletin #338. 1962 pp. 81-99.
47. Fordonsvagningar (Weighing of Vehicles) Metodik Och Apparatur. SWEDISH ROAD BOARD AND SWEDISH ROAD RESEARCH INSTITUTE. Stockholm, 1963.

See also: 24

Theory

VEHICLE AND ROAD DYNAMICS

48. Investigation of Stresses in the San Leandro Creek Bridge, UNIVERSITY OF CALIFORNIA. Institute of Transportation and Traffic Engineering.

Research Report No. 13 & Appendices to Research Report No. 13 A.
May 1953.

49. Stress Measurements, San Leandro Creek Bridge, ROY W. CLOUGH and C. E. SCHEFFEY, Transactions of the ASCE. Vol. 120, pp. 939-54, New York, 1955.
50. WASHO Road Test, Special Observations & Measurements - Load Shift. HIGHWAY RESEARCH BOARD. Special Report 22, Part II. 1955, pp. 170-174.
- *51. A Comparison of Methods Used for Measuring Variations in Loads Transferred Through Vehicle Tires to the Road Surface. R. C. HOPKINS and H. H. BOSWELL. "Public Roads." Vol. 28, No. 10. p. 221. / October 1957.
52. Vibration of Simple Span Highway Bridges. J. H. BIGGS, H. S. SUER and J. M. LOUW, Transactions of ASCE. Vol. 124, pp. 291-318, New York, 1959.
- *53. Dynamic Forces Exerted by Moving Vehicles on a Road Surface. R. P. H. BONSE, and S. H. KUHN. Highway Research Board Bulletin #233. 1959.
54. Highway Characteristics as Related to Vehicle Performance. BAYARD E. QUINN and T. W. DEVRIES. Purdue University, Lafayette, Indiana. January 1960.
- *55. Preliminary Analysis of Road Loading Mechanics. G. J. FABIAN, D. C. CLARK, and C. H. HUTCHINSON. Cornell Aeronautical Laboratory, Inc. Buffalo, New York. 1960
56. Computer Simulation of Vehicle Motion in Three Dimensions. I. J. SATTINGER, and D. F. SMITH, Report 2910-10-T. Special Projects Group. Willow Run Laboratories. University of Michigan. Ann Arbor, Michigan. May 1960.
57. A Method for Introducing Dynamic Vehicle Loads into the Design of Highways. BAYARD E. QUINN and R. VAN WYK. Purdue Research Foundation. Purdue University. January 1961.
58. On the Kinetic Behavior of Roads. DANIEL C. CLARK. Cornell Aeronautical Laboratory, Inc. Buffalo, New York. January 1961.
59. Effect of Speed Upon Highway Vehicle Reactions. BAYARD E. QUINN and D. R. THOMPSON. Report No. BPR-610609-4. Purdue University. Division of Mathematical Sciences.
- *60. Effect of Pavement Condition Upon Dynamic Vehicle Reactions. BAYARD E. QUINN and D. R. THOMPSON. Purdue Research Foundation. Purdue University. January, 1962.
61. Dynamic Behavior of Simple Span Highway Bridges. ROBERT K. WEN and A. S. VELETSOS. Highway Research Board Bulletin #315, 1962, pp. 1-26.

62. Measuring Dynamic Vehicle Loads. JOHN W. FISHER and H. C. HICKINS.
Highway Research Board, Special Report 73, The AASHO Road Test:
St. Louis Conference Proceedings, 1962. pp. 138-148.
63. Dynamic Studies of Bridges on the AASHO Road Test, Highway Research
Board, Special Report #71, June 1962. pp. 48-81.
64. Comparison of Different Methods of Determining the Dynamic Wheel Load.
O. BODE, et. al. Deutsche Kraft No. 131. 1959. Translation No.
1/63 Monthly Summary of Engineering Literature, Motor Industry
Research Associates. Lindley M. Nuneaton, Warwickshire, England,
January 1963.

The original publication in German:
Vergleich Verschiedener Verfahren zur Feststellung der dynamischen
Radlast. OTTO BODE et. al. "Deutsche Kraftfahrtforschung Und
Strasseneurkehrtechnik." Heft 131, 1959. 33 pp.

A summary of this work may be found in:

"Highway Research Abstracts." HIGHWAY RESEARCH BOARD. Vol. 33,
No. 7. July 1963. p. 2.

65. Analysis of Dynamic Behavior of Roads Subject to Longitudinally Moving
Loads. WILLIAM E. THOMPSON. Cornell Aeronautical Laboratory.
Buffalo, New York, January, 1963.
66. Axel Trycksmatningar: Sidolutningens och Centrifugalkraftens Inverkan
Pa Matnoggrannheten, STIG EDHOLM and H. NORRBY, Preliminary Report #3,
Swedish Road Research Institute, 1963.

See also: 74

Instrumentation

TRANSDUCERS

67. Subgrade Support Characteristics, Experimental & Theoretical, R. C.
GELDMACHER, et. al., Purdue University Joint Highway Research Project:
Lafayette, Indiana. February 1957.
68. Techniques for Protecting and Waterproofing Resistance Wire strain Gages.
MILLS DEAN III. Report #797 (Revised Edition) Instrument Division,
David Taylor Model Basin, Navy Department. October 1957.
69. Measuring Strain to 1000°F, Instruments and Control Systems, Vol. 33, 1166,
July 1960.
70. Load-Cell Weighing to 0.05%, Instruments and Control Systems, Vol. 33,
1152, July 1960.

SENSING & RECORDING DEVICES

71. The WASHO Road Test - Design, Construction and Testing Procedures, HIGHWAY RESEARCH BOARD, Special Report No. 18, Part I, pp. 30-39: 1954.
72. Toll Collection Systems, INTERNATIONAL BUSINESS MACHINE CORP., New York 20, New York.
73. Standard Electronic Units Interconnect to Provide Flexible Digital Recording, R. C. HOPKINS, Highway Research Board Meeting. January, 1960.
74. Feasibility Study, Automatic Weighing of Vehicles in Motion and Collection of Traffic Data by Electronic Methods, EPSCO, INC., Cambridge, Mass. Michigan Project 52F-26 March 1961.
75. Reduction of Recorder Sensitivity in Preloaded Electronic Weighing Systems. RUSSELL E. PUCKETT and J. E. GOVER. Bulletin #67, Engineering Experiment Station, University of Kentucky, Lexington, Kentucky. March 1963.
76. Comparison of Two Methods for Preloading Electronic Scales, RUSSELL E. PUCKETT and J. E. GOVER, Public Roads, June 1963, pp. 181-185.

See also: 17, 18, 20, 22, 23, 24

Selected References

1. Structural Design for Dynamic Loads, C. H. NORRIS, et. al., New York, McGraw-Hill Company, 1959.
2. The Theory of Vibrations for Engineers, E. B. COLE, New York, Macmillan Company, 1957.
3. Elements of Strength of Materials, S. TIMOSHENKO and G. H. MAC CULLOUGH, New York, D. Van. Nostrand 1950.
4. The Strain Gage Primer, CHARLES PERRY, New York, McGraw-Hill Book Company, 1955.
5. Characteristics and Applications of Resistance Strain Gages, NATIONAL BUREAU OF STANDARDS. Circular 520, Govt. Printing Office, Washington, D.C., February 1954.
6. Strain Gages, Theory and Application, J. J. KOCH, Phillips Technical Library, Eindhoven, Holland: 1952.
7. Electric Resistance Strain Gages, W. B. DOBIE and P. C. G. ISAAC, English Universities Press, Ltd.: 1950.
8. Principles of Electronic Instruments, G. R. PARTRIDGE, Prentice-Hall, Inc., Englewood Cliffs, N. J., 1958.

9. Electronic Fundamentals and Applications, JOHN D. RYDER, Prentice-Hall, Inc. 1959
10. Electronic Engineering, SAMUEL SEELY, McGraw-Hill Book Co., New York, 1956.
11. Fundamentals of Electron Devices and Circuits, H. R. WEED and W. L. DAVIS, Prentice-Hall, 1959.
12. Pulse and Digital Circuits, MILLMAN, JACOB, and HERBERT TAUB, McGraw-Hill, 1956.
13. Control System Components, JOHN E. GIBSON and FRANK B. TUTEUR, McGraw-Hill, 1958.
14. Sampled-data Control Systems, JOHN R. RAGAZZINI, McGraw-Hill, 1958.
15. Transients in Electrical Circuits, G. V. LAGO and DONALD L. WAIDELICH, The Ronald Press Co., New York, 1958.
16. Experimental Stress Analysis, M. B. MOORE, New York, Prentice-Hall, Inc. 1954.
17. Statistical Theory in Research, R. L. ANDERSON and T. A. BANCROFT, First Edition, New York, McGraw-Hill, 1952.

3. Developments in Electronic Weighing. NATIONAL BUREAU OF STANDARDS.
Miscellaneous Publication #199. May 1950.

This paper discusses electronic scales and their application to commercial static weighing. One installation described is a livestock scale consisting of a platform, 26 feet long, supported by four 50,000 lb. capacity load cells. The indicating unit includes a dial readout operated by a servo-mechanism which is energized by the amplified output of the load cell unbalance. The indicator is connected to an automatic printing unit. This unit records a sequence number, the dial reading, the date and time of day, the number and type of animals and the seller's name. The variable items are preset into the printer by a system of manually operated keys. The capacity of the scale is 32,000 lbs. Weights can be determined to the nearest 5 lbs. Other features of the scale are:

- (1) A balancing control knob or push button for re-balancing the scale after removal of the load.
- (2) A damping device on the indicator to provide a steady reading when weighing restless livestock.
- (3) A standardized and calibrated replaceable servo mechanism in the indicator unit to facilitate servicing and minimize interruptions in weighing.

The advantages of the electronic scale over the conventional lever type scale were concluded to be:

- (1) No moving parts (except in the indicator unit) to wear out.
- (2) Light weight - the 32,000 lb. capacity scale, excluding platform, weighed only 85 lbs.
- (3) The indicator and printer could be located several hundred feet from the scale.
- (4) Instant response - no "oscillation period" before weights could be determined.
- (5) Vacuum tubes used in the equipment were of the ordinary radio type and could be easily replaced.
- (6) Sensitivity of the scales did not decrease with an increase in loading.
- (7) The load-error relationship was constant throughout the load range of the scale.

9. Weighing Vehicles Static and In Motion by Electronic Scales. O. K. NORMANN.
SAE Transactions. Vol. 63. 1955. p 373.

This paper was presented at the SAE National Transportation Meeting in Boston on October 18, 1954. It consists, generally of a review of vehicle weighing methods with particular emphasis on the results of the Bureau of Public Roads experiments in electronic weighing.

Electronic weighing of static loads is illustrated by a description of an installation in Detroit, Michigan. This scale, 60 ft. long, 10 ft. wide

and having a capacity of 150,000 pounds is used to determine gross and net weights of cement trucks. It features an automatic print-out of the exact weight of cement loaded.

Weighing a 200 truck sample for planning data by the conventional loadometer method costs from \$100 to \$150 per day. Many truck drivers will use other routes to avoid the delay of being stopped for weighing even though no law enforcement is involved. Present enforcement weighing practice is to stop and weigh all trucks except those that are obviously empty. The percentage of overloaded trucks detected at 23 Illinois weighing stations over a 14 week period was only 0.2%. This meant that, in this case, over 1,250,000 trucks were stopped unnecessarily.

Facts such as these prompted the Bureau of Public Roads to build the first electronic scale for weighing vehicles in motion. This scale and the attendant testing are described in Highway Research Board Bulletin #50. The author also mentions the attempted use by the Bureau of Public Roads of a 600 pound wooden platform and certain manufacturer's experimentations with the use of one and two load cell systems.

An oscillograph is recommended as a recording instrument because a permanent record is obtained. Equipment has been developed which records truck weight as a certain weight "class", determines if any axles are loaded beyond the legal limit and prints this information on a punch card. Other devices are available which sound a gong or flash a light whenever a vehicle with excessive axle loading crosses the scale.

Further accuracy statistics based on the Bureau's research are quoted as follows:

- (1) 60% of the weights obtained of vehicles moving at normal speeds were within 5% of the true weights. Maximum percent of error was 10%.
- (2) Total tonnage of vehicles using a highway can be determined to within 2% of the total obtained from static weighing.

The author's conclusions are similar to those reached in HRB Bulletin #50. He does, however, suggest other uses of the electronic scale in:

- (1) Measuring impacts from surface roughness and uneven tires.
- (2) Testing the efficiency of truck suspension systems in reducing impact.
- (3) Other related areas of research.

12. Truck Motion Weighing Report T-38. J. J. HEATLEY CO., Smithtown, N.Y. 1956.

This is a non-technical description of dynamic weighing methods, employing the Cox & Stevens equipment. It was written to acquaint the trucking industry with the operation and location of electronic scales then in existence. The paper is well illustrated with maps, photographs and diagrams.

Two types of motion-weighting equipment were in use; the research unit for collecting weight data for planning and the overload detection unit. The platform sizes were 3' x 11' for the research unit and 7' x 11' for the overload detector unit. The load cell used was 3" high x 2 3/4" in diameter and had a capacity of 50,000 lbs.

The indicator for either type unit could be placed as much as 200 ft. from the platform site - its operation was automatic. The research unit required an operator. The overload detector operated automatically.

Vibration of the vehicle increased with speed, thereby causing variations in the dynamic weights recorded by the overload detector and causing it to indicate an overload where none existed. The drivers were then required to cross the detector at slow speeds.

The detector platform was equipped with two pairs of indicating treadles. If the truck wheels did not pass over all four treadles, an overload indication was flashed and the vehicle was directed to "go to scale" whether it was illegally loaded or not. Straddling the scale was therefore discouraged.

The effect of accelerating when crossing the platform was to increase the rear axle loads. Deceleration increased the load on the tractor drive axles. Recommended practice was to coast over the platform at slow speed.

Overload detector installations are described in the report for the following locations:

- (1) Woodbridge, Va. on U S. Route # 1 - a test site of the BPR. This was a later version of the original experimental set-up.
- (2) Minneapolis, Minn., Route #12.
- (3) Minneapolis, Minn. - Route #100 - connected to the same scale house as (2).
- (4) St. Paul, Minn. - Route #12.
- (5) Between Wallingford and Meridien, Conn. - Route #5 - Manufacturer's experimental station.

Research type electronic scales are described generally and locations listed for:

- (1) Shirley Highway, US #1, Washington, D.C. - the USBPR experimental scale.
- (2) Tama, Iowa, US Route #30 - operated seasonally to check truck weights in both directions. Nine additional units were on order at the time this report was published.
- (3) Oregon - located on connector between US 99W and 99E, near Oregon City.

16. Weighing Vehicles in Motion. O. K. NORMANN and R. C. HOPKINS. Highway Research Board Bulletin #50. 1952

This bulletin reports the pioneer efforts of the Bureau of Public Roads to develop an experimental electronic scale for weighing moving vehicles. Many types of electrical and mechanical devices were investigated before it was decided to use a commercially developed "load cell" employing the resistance wire strain gauge. Details concerning the preliminary experiments are not given in this report.

The original BPR electronic scale was constructed in the right hand south bound lane of the Shirley Highway near Woodbridge, Virginia. Construction of the pit and platform slab was completed on May 7, 1951. A lever system static scales located nearby was used to check the electronic scale results. Ten inch steel channels were used as forms for the 30' x 12' section of concrete pavement in which the scale platform was to be located. Care was taken to provide a smooth approach to the slab from the adjacent pavement.

The scale platform was a concrete slab 3' x 10' x 12" thick poured in a form made up of 12" - 35#/ft. channels and reinforced with 1" bars @ 24" on center and 2 layers of welded wire mesh.

The 30" deep pit was built to allow a 3/4" clearance between the slab edges and the pit walls. A 1" x 3/4" rubber strip was inserted in this space to provide a seal. Horizontal movement of the scale platform was controlled by a system of brackets and turnbuckles mounted on the underside of the platform slab. Pilasters were provided at each corner of the pit for the load cells.

The load cell used in this installation was manufactured by the Cox & Stevens Aircraft Corporation, Mineola, New York. Four of these cells constituted the strain-measuring section of the scale. The load cell is composed primarily of a set of 4 short steel columns to which are bonded resistance wire strain gauges. Dummy columns with attached strain gauges are included in the cell to provide for temperature compensation. Each cell is in itself a complete Wheatstone bridge and any change in the loading of the cell causes a change in the resistance of the wire strain gauges, thereby unbalancing the bridge. The four load cells were connected in parallel so that the total unbalance of the cells could be measured. An accurate weight could then be determined regardless of the transverse placement of the vehicle on the platform. The load cells and the electronic measuring equipment used in this study were part of the Cox & Stevens Aircraft Weighing Kit used for the static weighing of aircraft. Each cell was accurate to within 10 pounds for weights up to 50,000 pounds.

The unbalance of the cells was amplified and presented on the screen of an oscilloscope tube as a pattern representing the axle weight of the vehicle. A record of the weight patterns was obtained by photography. A square wave generator was included in the circuitry so that definite time intervals could be shown on the gridded screen of the oscilloscope tube, thereby permitting vehicle speed and axle spacing to be measured. The factory-calibrated Weighing Kit permitted the scale to be artificially loaded by unbalancing the bridge circuit in 5,000 lb. steps through the use of a "load switch." Thus it was not necessary to calibrate the scale by placing known weights on the platform.

Initial accuracy tests of the scale were conducted using a loaded two-axle dump truck. This truck was weighed statically on a conventional lever-system scale, then weighed in motion at speeds of 10 to 50 m.p.h. on the electronic scale. The maximum difference between static weight and weight-in-motion was 400 pounds or 8.5% for the front axle and 1100 pounds or 8.7% for the rear axle. The average error was about 5%. The speed of the vehicle seemed to have no effect on the magnitude of the error.

Trucks actually using the highway were also weighed as a part of the initial tests. These trucks were later check-weighed at the lever system scale. Large errors were noted for trucks with dual axles. The speed of the truck did not consistently effect the accuracy of the first axle weights. However, the size of the error for the second and third axles increased greatly with an increase in speed. The error for the third axle was greater than that for the second axle at the higher speeds.

These preliminary tests indicated that impacts were being transmitted to the load cells due to a movement or vibration of the slab as the vehicle crossed the scale. This was particularly noticeable in the weight recordings of the second and third axles of a three axle truck crossing at high speed. Adjustment of the oscilloscope spot spread out the weight patterns obtained under these conditions and enabled a more detailed analysis. The slab appeared to be either moving horizontally, rocking on the four supporting load cells, or to be still vibrating from the passage of the first axle of the tandem at the time the second axle passed. In an attempt to alleviate the errors, the horizontal motion was checked by welding the restraining tie-bars to their brackets under the slab and on the pit walls. The tops of the load cells were leveled so that each cell supported an equal share of the load. It was necessary to maintain the tops of the load cells within one thousandth of an inch of the same elevation in order to prevent impacts due to the rocking of the slab. Observations of the width of the zero indication on the tube after a vehicle had passed indicated that the slab was vibrating at a frequency of 80 to 100 cycles per second.

After the slab was leveled and secured against horizontal movement, a second series of tests was conducted; weighing moving trucks in the normal traffic stream. Only about fifty percent of the trucks passing the study location would cross the scale with all tires on the ten foot platform. A transverse placement detector was used to eliminate from the record those vehicles with one or more tires off the scale. Weight recordings were made under controlled speeds of 10, 20, 30 & 40 m.p.h. and at normal highway speeds which averaged 48.4 miles per hour.

The results of these tests showed an average error of 6.5% for single axles, 4.4% for the first axle of a dual axle and 16.7% for the second of dual axles. Once again, speed variations had no consistent effect. Since the electronic scale recorded weights which were sometimes higher and sometimes lower than the static weights, the cumulative weight of all the trucks compared favorable with the gross tonnage as recorded by the static scale. The actual percentage of error was 1.5% for the total weight of all single axles and 4.2% for dual axles.

To further reduce vibrations in the slab, vertical bolts were installed through the slab to permit preloading by tightening the nuts against the top of the slab. Up to 6,000 pounds tension could be applied to each of the three bolts which were located at the center and ends of the slab. The pre-loading produced smoother oscilloscope patterns and reduced the size of the errors by about 50%. The agreement between gross tonnage obtained from moving and static weights was remarkably good after preloading. The following conclusions were reached:

- (1) For static weighing, the electronic scale is as accurate as the lever system scales.
- (2) The data concerning different axle and truck load frequencies and gross tonnage per section of highway as obtained from the electronic scale are sufficiently accurate for highway planning purposes. Speeds and axle spacings may also be measured.
- (3) It is possible, using the electronic scale, to sort out vehicles with axle loads near or above the legal limit without interfering with the normal flow of traffic.
- (4) Improvement in accuracy is possible through re-design of some of the scale components.

The following design improvements were recommended by the authors of this report:

- (1) Reduce bending and vibrations in the scale platform by placing the load cells 6 1/4 feet apart rather than 10 feet. This would place the cells more nearly under the truck wheels.
- (2) Provide additional tie bars at the pavement surface to reduce horizontal motion.
- (3) Re-design the scale to provide three-point suspension. This would alleviate slab leveling difficulties.
- (4) Waterproof the load cells. The waterproof jackets and dehumidifying agent supplied with the cells did not prevent moisture accumulation and a resultant decrease in accuracy of the strain gauges.
- (5) Substitute a pen or heated stylus recorder for the oscilloscope and camera.
- (6) Design the control system for automatic operation.

17. An Apparatus for Measuring, Classifying and Counting the Wheel Loads of Moving Vehicles. J. J. TROTT and P. J. WILLIAMSON. Department of Scientific and Industrial Research. Road Research Laboratory (Great Britain). Research Note No. RN 34871JJT.PJW. May 1959.

In 1958, the British Road Research Laboratory built and tested a small lightweight dynamic scale. The scale is in two separate units; the weigh-bridge and the weight classifying and counting equipment.

The weighbridge consists of a 2' x 6' x 7 1/4" platform fabricated of 3" x 6" I beams and 3/8" plate and supported on 4 load cells in a shallow (7 3/4" deep) concrete pit.

Special load cells were built for this scale. A cylinder of beryllium-copper 3" long and 1" in diameter was bored out to leave a net cross sectional area of 1/2 square inch. Foil type strain gages having a resistance of 55 ohms each were bonded to this hollow column. Four gages were used for each cell, two parallel to and two perpendicular to the column axis. Hardened steel caps were provided at each end of the cell to assure uniform load application. The entire assembly was enclosed in a protective covering of waterproofing wax with an outside sheath of brass.

Load from the platform was transmitted to the cell through 3/4" diameter steel balls at each end of the cell. Levelling was accomplished by raising or lowering the upper bearing seat which is threaded into the load cell housing. Access to the 4 levelling screws is gained by removing the fore and aft sections of the platform cover plate.

The British researchers considered it necessary to include a static compression or preloading device for the platform. This was done by anchoring three bolts to the bottom of the pit. Each bolt passes through the lower side of the platform and into a heavy spring. Pre-load was applied by tightening the nut on each bolt, thereby compressing the springs which exert a downward force on the platform and the load cells.

The weighbridge was placed in the pavement so that its near end was one foot from the curb. This position picked up the near-side wheel of practically all the passing vehicles. The platform width was set at 2 feet so that individual wheel loads of dual axles could be separated. This would require an axle to axle time of 0.085 seconds for dual axles five feet apart at 40 m.p.h. Actual time between one wheel leaving and the next one coming on the platform, however, was only about 0.05 seconds for the two foot platform width. It was therefore necessary to provide electronic equipment capable of distinguishing individual electrical pulses at this minimum time interval. It was also concluded that, due to the remote location of some of the proposed installations, a battery-operated unit would be required.

The problem was solved as follows:

1. The output, under load, of the platform's 16 strain gages was fed through the usual Wheatstone Bridge circuitry, directly to a mirror galvanometer.
2. This small voltage caused the galvanometer to deflect an amount proportional to the applied load.
3. A light beam, reflected from the galvanometer mirror was made to pass over a bank of 10 photoelectric cells.
4. The pulse of voltage generated by the photoelectric cells was used to operate high speed relays which caused a mechanical counter to register an individual wheel load in its proper weight bracket and in all brackets below that particular weight class.
5. The number of wheel loads in a given weight class was then obtained by subtraction.

The setup was adjusted to record wheel loads in 1,000 lb. steps. Accuracy of the recordings, which was controlled by the photo-cell apertures and the distance between them was about ± 111 lbs.

Errors in the dynamic weights were attributed to vibrations in the platform, overshoot of the galvanometer and vibrations in the applied wheel load due to pavement roughness and vehicle pitch and roll. A calibration procedure showed no significant platform vibrations or overshoot. Apparent vehicle weights were found to increase about 20% for a speed increase of 0 to 30 m.p.h. Maximum values occurred at 5 and 30 m.p.h., the minimum at 20 m.p.h. These differences were considered to be due to the undulations of the vehicle. The need for a smooth approach to the platform was emphasized.

Some difficulty was encountered due to the "zero drift" of the apparatus caused by the effect of temperature changes on the strain gages. Manual and automatic methods were devised for correcting or compensating for this drift.

Further research is planned to determine the sizes of errors due to pavement roughness and speed. The length of smooth approach needed for best results will be determined. Once again, the general conclusion was that the electronic scale will record the actual applied wheel load and that this is the load for which the highway should be designed.

18. Die Automatische Achlastwaage bei Grunbach (Remstal). W. SCHWADERER & W. REIMUND - "Strasse und Autobahn". 1959. pp. 41-47

In 1958 engineers of the Otto-Graf Institute, Stuttgart, designed and constructed a dynamic scale to be used in the collection of axle load data on the test road near Grunbach. This scale represents a departure from the earlier concept of a monolithic platform in that it consists of a steel platform split lengthwise into two sections of equal width. The outside edge of each section rests, near the corners, on hinged supports. The contiguous edges are mutually supported by two strain gage load cells. The platform is preloaded by two heavy coil springs.

The load cells' output as a vehicle moves over the platform is recorded on an oscillograph tape in the form of an inverted "vee". The peak of this wave form is for all practical purposes a point sample of the varying load applied to the platform by the moving axle as it crosses the lengthwise split at the scale's center. In addition to providing an easily read weight indication on tape, the discrete output of the "broken bridge" also lends itself to a relatively simple electronic sorting process when the grouping of axle loads into various weight categories is desired.

The German group made a detailed investigation of the "impact coefficient" (dynamic weight/static weight) from a large sample of trucks crossing the test installation. The ratios varied from 1.0 to many times the static load. The variations were as likely to be negative as positive. Overall "error" or difference for the Grunbach scale was about $\pm 5\%$. Much emphasis was placed on the importance of a smooth approach surface to the scale platform.

The broken bridge design was adapted by the Kentucky research team and a prototype has been extensively tested during the course of the project. A more detailed description of this scale and the test results may be found in the previously noted references.

23. Weighing Vehicles in Motion. S. P. MAGGARD. Unpublished Thesis. Master of Science in Civil Engineering. University of Kentucky. 1957

Experience with existing electronic scale installations indicated the need for developing a simpler, more economical means of weighing moving vehicles. All of the then existing installations used a platform supported

by load cells. The wheel load was determined by the change in strain in the columns which made up the load cell. This strain was measured by resistance wire strain gages bonded to the columns. Weight recordings were usually made on an oscillograph employing a heated stylus.

This thesis proposes the use of a concrete platform on simply supported steel beams. Strain gages would be attached to the exposed flanges of the beams to measure the strain due to the tensile and compressive stresses induced by bending as the vehicle crosses the platform. A recording oscilloscope is recommended as the most practical device for recording these strains.

This proposal was checked through the use of the scale platform of an existing static weighing station near Georgetown, Kentucky. The scale platform, designed for the weighing of one wheel was 5'-11" long in the direction of traffic and was 4'-11" wide. It consisted of a 3" concrete slab on a grillage of 4 transverse 8"-I beams, supported in turn by 2-8" I beams with well oiled rod and groove supports at each end. A 36" deep pit provided access to the underside of the platform.

After surface preparation, type A-1, SP-4 strain gages were applied to the two supporting beams and waterproofed with a special wax and Scotch electrical tape. Extremely wet conditions in the pit beneath the beams made this waterproofing a vital part of the procedure.

Preliminary tests showed the necessity for devising a Wheatstone bridge circuit which would be independent of the transverse placement of the wheel on the platform. This was accomplished by placing two strain gages on the top and bottom flanges of each beam. Gages in corresponding positions on the two beams were placed in the same arm of the bridge. Gages under compression on the top flange were placed in an opposite arm of the bridge from the gages in tension on the bottom flange. This resulted in a magnification of the true resistance change as recorded by the galvanometer, provided for temperature compensation and eliminated the need of considering transverse wheel placement.

The galvanometer used in this study was of the portable recording type and was mounted in the rear seat of a four door passenger car owned by the Kentucky Department of Highways Research Laboratory. The recording was done by a light beam reflected from a mirror mounted on the galvanometer coil to a light sensitive moving film.

Tests were run on this scale using a single axle dump truck with a gross weight of about 15,000 lbs. Due to the physical set-up of the scale platform, only the wheel loads of the right side of the vehicle were weighed. Static wheel loads were determined before and after each run by driving the truck over the scale at creep speed. This was necessary because of the difficulty of recording the galvanometer deflection for a stationary load.

The weighing tests were conducted as a series of three runs each at speeds of 5, 10, 20, 30, 35, 40, and 45 m.p.h. Additional tests at 10, 20, and 30 m.p.h. were run with the truck wheels passing over a 3/4" obstruction

before striking the platform. Starting and stopping the test runs and recorder were done by manual signaling. These tests were similar to those conducted by the ITTE in their study of the stresses in the San Leandro Creek Bridge (48, 49).

In analyzing the results of the tests, it was assumed that the galvanometer deflection was a linear function of the load applied to the beam. This relationship can be derived by application of the laws of static equilibrium. The percentage increase in load due to impact was determined by simply comparing the static and dynamic wheel loads directly from the tape output.

The wheel loads obtained from the three runs at a given speed were in fairly close agreement. Occasional differences were attributed to local electrical interference with the operation of the galvanometer. Use of the 3/4" high obstruction resulted in impacts which averaged 25% above the static weights. This percentage was in agreement with that obtained in the San Leandro Bridge tests using much more elaborate equipment.

Conclusions were reached that:

- (1) The method tested is a practical way of measuring dynamic wheel loads.
- (2) The apparatus could be improved by eliminating the transverse beams and lengthening the platform to about 8'-6".
- (3) Impact factors may exceed the 30% usually specified for design.

29. Weighing Trucks in Motion (A Report). Iowa State Highway Commission. October 1954.

One of the earlier experimental installations of the electronic scale was made by the Iowa State Highway Commission on U.S. 30 near Tama, Iowa in October 1954.

The scale used was the Cox & Stevens Model TR-1 consisting of a 3' x 10' free floating platform supported by four load cells. Sensing and recording were done by a Sanborn Recorder and Amplifier, employing a heated stylus and constant speed moving tape. Automatic starting and stopping of the tape was accomplished by installing a pneumatic switch operated by road tubes spaced 52.8' each was from the scale. The function of the start and stop tubes could be reversed by a switch, thus permitting vehicles approaching from either direction to be weighed.

The heated stylus recorded the start and stop of each weighing operation as a pip mark, and the weight impulse of each axle as a vertical deflection. Tables are included in this report that permit calculation of speed and axle spacing based on the known tape speed (1.97 inches per second), the road tube spacing (52.8 feet) and the measured distance between weight impulses on the tape.

The axle weights were determined by the deflection of the stylus from the zero reading. The relationship between weight and deflection was neither linear nor constant. This necessitated frequent calibration of the sweep of the stylus.

The electronic equipment for this initial installation was mounted in a used school bus since the scales were to be used primarily to gather continuous truck weight data for planning purposes.

The results obtained from the first Iowa scale were very erratic. Comparison with weights obtained at a lever-system scale showed that 20% of the vehicles were over weighed by more than five percent. Only 5% were underweighed by more than five percent. Fifty percent of the moving vehicle weights were within 2% of the static weights.

The following reasons were given for these discrepancies:

- (1) The small size of the weight scale readings on the tape.
- (2) Leveling difficulties with the scale platform and the load cells. Rocking of the slab was reduced by using shims to level the platform.
- (3) Variations of up to 1000# in the magnitude of the stylus sweep on the Sanborn Recorder.

30. Iowa Research Scales Go Electronic. J. J. HEATLEY. "Traffic Engineering" December 1957. p. 18-19. 50.

Three years of experimentation with a single electronic scale installation convinced Iowa highway engineers that dynamic weighing was the most practical way of obtaining weight data for planning purposes. Nine additional units were scheduled for installation by 1958.

Iowa's Traffic & Safety Engineer felt that the major advantages of electronic weighing were that the safety of the traffic survey crew was enhanced and that the crew could be reduced in size, thereby saving money.

The three year experimental period resulted in these revisions in equipment and operations:

- (1) The development of a portable indicator recorder unit capable of providing axle weight data from any one of 10 scale installations throughout the state.
- (2) The modification of a used school bus to house the indicator recorder and other equipment such as barriers, signs, spare parts, etc. When not in use, the bus and its equipment could be stored in a state garage, thereby affording much better protection for the delicate electronic apparatus than could be provided by a permanent road side installation.
- (3) Traffic from both directions was weighed by the use of a system of channelizing barriers. The survey period used was usually eight hours. With the single lane operation, maximum speed over the scale was 15 m.p.h. No appreciable delay to through traffic was noted.

- (4) Weatherproof junction boxes were placed at each scale site. The bus-mounted equipment could be plugged-in, barriers erected and the 3-man crew ready to operation within about 15 minutes of the arrival time at the site.

Iowa engineers' have reached these conclusions about electronic dynamic weighing:

- (1) The axle weight accuracies obtained are acceptable. It is senseless to "compare" static and dynamic weight recordings since many uncontrollable variables influence the weight reading of moving axles.
- (2) The electronic scale accurately records the loads actually applied to the highway surface as the truck moves along the road. The fact that the electronic scale weighs "high" when compared to static scales is an indication that dynamic axle weights rather than static loads should be used in pavement thickness design.

Difficulties were encountered in obtaining accurate readings from the tape due to the compressed scale in the direction of the stylus sweep. A digital type read-out was thought desirable as it would eliminate the coding and card punching required with the tape.

There were no maintenance problems with the original installation even after three years. The load cells remained in balance and it was not thought necessary to remove them for inspection and servicing. The new installations were to include an additional leveling strut beneath the platform.

Completion of the Interstate Highway System in Iowa would require sixteen additional electronic scales. Thus a total of 26 installations would be needed to provide current data on axle weights and frequencies on the major truck routes of the state.

36. Electronic Weighing Equipment, STATE OF MINNESOTA, DEPARTMENT OF HIGHWAYS (Report), November 1956.

The installation and use of three electronic scales by the State of Minnesota is described in this report.

After inspecting the BPR electronic scale near Washington, D.C., officials of the Minnesota Department of Highways decided to make use of commercially developed weighing and detecting units in one or more of these combinations:

1. Use of the static-weighing electronic scale for enforcement purposes.
2. Use of the detector alone to secure weight data for research and planning.
3. Use of the detector to cull out violators for check weighing on the static scale.

The first installation described was of the third type listed above. The 12' x 8' detector platform was set in the pavement about 1500 ft. from and in view of the static scale house. An overloaded vehicle passing over the detector caused an electric sign to flash on, directing the vehicle to go to the static scale. At the same time a warning light appeared to the scale house operator. The detector employed four load cells in conjunction with the usual starting and stopping strips and electronic recording devices. All controls and equipment were housed in a cabinet near the detector. Although the primary purpose of the detector was to detect axle weights exceeding some pre-set legal limit, it was also possible to obtain from a tape print-out, individual dynamic axle weights, axle spacing and speed.

The static scale consisted on a 10' x 10' platform supported on four load cells. The frame scale house was 16 ft. square and was equipped with a two way radio hook-up to state headquarters in St. Paul. Floodlighting was provided for the entire area as were "flip-up" speed limit signs and lane marking cones.

The cost of the St. Paul installation was \$28,490. This included the cost of the static scale and scale house. Fines collected from operators of overloaded vehicles detected at the station amounted to nearly \$15,500 during a three month period.

A second installation, west of Minneapolis included two detector platforms connected to a central static scale house. The detector scales were used to obtain planning and research data through the use of portable equipment which could be plugged into the detectors. Minnesota highway officials regarded the collection of this data as being of prime importance in the planning of future roads, and suggested that on these grounds alone, the cost of the electronic scale was more than justified.

It was planned to relate the dynamic axle weights of moving vehicles to the speed and static weight of the trucks observed in order to determine axle weight frequencies on a given length of road. This type of data would be very useful in many phases of highway design.

The following difficulties were encountered in the operation of the Minnesota installations:

- (1) Transverse vehicle placement: It was necessary to channelize the traffic passing the detector so that all the wheels of a given truck would pass over the platform.
- (2) High truck speeds: Speeds over 55 m.p.h. caused such high dynamic axle weight recordings that the stylus trace was not clear. The speed limit was set at 40 m.p.h. in the vicinity of the detector.
- (3) Cold weather made it difficult to maintain the heated stylus at the proper temperature. Insulated housing was provided for the instrument. This and other difficulties with the recording tape resulted in the adoption of the van-mounted portable set-up previously mentioned.
- (4) The weighing units required a good deal more attention than was at first anticipated.

37. Weighing Trucks in Motion and the Use of Electronic Scales for Research. W. W. STIFFLER and R. C. BLENSLY. Oregon State Highway Department. November 1955.

This is a detailed description of the installation and operation of the Cox & Stevens TR-1 electronic scale by the Oregon State Highway Department. The purpose of the installation was to obtain complete information on the weights and frequencies of axles and vehicles on a section of highway as a part of a long range pavement performance test conducted by the Department and the Bureau of Public Roads.

The scale was installed in September 1954 on a connecting road between US99E and US 99 near Oregon City. The ADT on this section was about 5000 VPD, 23% of the volume being composed of trucks. It was anticipated that the number of trucks would exceed 50% of the total in the future.

Two separate scales were installed so that both directions of traffic could be weighed. The cost breakdown for the installation was as follows:

First Scale (C&S TR-1)	\$ 3900.00
Second Scale (C&S TR-1)	\$ 3750.00
Pit and Building	\$ 2850.00
Calibration and Installation	\$ 1500.00
Total	<u>\$12000.00</u> (Approximate)

The scale platform was of reinforced concrete, 3 ft. wide, 10' 6" long, 15" thick and weighed 7000 lbs. The scale pit provided about 2 1/2 feet of headroom with the platform in place. Each load cell was supported on an individual leveling plate fitted with four leveling screws. Ball and socket joints at the top and bottom of each cell prevented bending from occurring due to lateral slab movement.

Rubber road tubes spaced on both sides of the platform and connected to air switches in the pit served as starting and stopping switches for the recording devices.

Much time and effort was required to bring the platform to an exact level position and at the same time keep the top even with the road surface. The leveling screws were adjusted until the recorded weights on each of the load cells were within 500 lbs. of each other. The space under the leveling plates was then filled with grout, thus preventing any further adjustments other than the use of shims. All wiring was placed in conduit and all joints sealed against moisture.

The scale was calibrated by static and in-motion weighing of a tractor and semi-trailer combination with known axle weights. A large trucking concern agreed to run their scheduled vehicles over the scale, thus providing a sizeable sample from which the accuracy of the scale was determined and correction factors calculated.

The most accurate values of axle weights were obtained by reading the stylus trace on the tape at the lowest point where the trace first departed

from a nearby vertical line. Overshooting of the stylus and impact on the platform were thought to be the causes of the erratic and unreliable trace above this point. Periodic calibration of the recorder was necessary because of instrument drift during operation. This was done by means of a load simulator. The weight recordings on the tape could be read only to the nearest 1000 pounds; no attempt was made to obtain closer readings.

As in the BPR tests, some difficulty was encountered in the weighing of tandem axles. It was determined that the combined weight on the pair was not equally divided when the vehicle is in motion. However, combined weights obtained electronically compared favorably with those from the pit scales.

An analysis was made of the accuracy of the electronic scale as compared to conventional scales. Correlation coefficients and standard errors were calculated for the following conditions:

- (1) Comparison of weights of all axles, using the electronic scale average for a tandem pair -
Correlation coefficient - 0.96
Std. error - 1370 lbs. (Northbound)
Std. error - 1210 lbs. (Southbound)
- (2) Comparison of Gross Weights - Correlation coefficient - 0.99
Std. error - 2700 lbs. (Northbound)
Std. error - 3600 lbs. (Southbound)

Correction factors of + 1000 lbs. and - 1000 lbs. were computed for weights over 4000 lbs. on the northbound lane and for all axles on the southbound lane, respectively. It was concluded that this accuracy was sufficient for research purposes but not for law enforcement.

Speed and axle spacing measurements were attempted with rather disappointing results. Adjustment or modification of the equipment would be necessary to obtain reliable measurements of these variables.

Maintenance problems encountered during the first months of operation of this facility may be summarized as follows:

- (1) Vacuum tube failures. Installation of voltage regulators seem to have solved this problem.
- (2) Moisture condensation on the equipment in the scale pit. The pavement-platform joint was sealed and a heater and dehumidifier were placed in the pit.
- (3) Various electronic troubles could have been prevented by the retaining of a competent radio technician.

A weighing program, using the electronic scale, was conducted for a four month period. The sampling period used was 2 a.m. to 10 a.m. on Mondays through Thursdays. This provided the most representative sample of axle weights. Expansion of the sample resulted in an average error of less than 10%.

Recommended improvements for future installations were as follows:

- (1) Modify the equipment for unattended, full time operation. This would require the use of pressure sensitive devices other than road tubes to start and stop the equipment only for axles weighing over 4000 lbs.
- (2) Follow the suggestions of HRB Bulletin #50 for fixing the slab horizontally.
- (3) Provide equipment to maintain the pit at a nearby constant temperature and humidity.
- (4) Locate the scale near existing pit scales or loadometer sites.
- (5) Install an automatic time-of-day stamping device for the tape.
- (6) Construct a device for easier leveling of the load all tops.
- (7) Install a voltage regulator.

46. Methods of Traffic Measurement - Determination of Number and Weight of Vehicles. S. EDHOLM. Highway Research Board Bulletin #338. 1962. pp. 81-99.

In 1960, the Swedish Road Board requested the National Swedish Road Research Institute to design and construct a portable electronic scale to be used in the collection of dynamic axle load data at approximately 200 points distributed over Sweden's highway system. The resulting device consists of a small steel platform (1' 8" wide, 4' 7" long and 4 3/8" deep) which is bolted to three supports set in a shallow pit near the right edge of the traveled way. The load sensors are three cantilever beams located inside the box-like platform at the three support points. Four strain gages mounted on the free end of each cantilever produce (under load) an out-of-balance voltage which is proportional to the applied dynamic weight. The total load on the scale is represented by the sum of the unbalanced voltages from the three beams.

The scale output is amplified and fed into the galvanometer loop of a direct recording instrument which causes a fine ink line to be traced on paper tape moving at a constant speed. The tape drive mechanism is started and stopped by a diaphragm switch that is actuated by the passage of a vehicle over rubber road tubes located fore and aft of the scale platform.

Some unique precautions were taken in the design of the electrical system to insure dependable automatic operation; these included: a thermostatically controlled heater for the interior of the instrument case and a load-simulating resistance connected in parallel with each of the load beam bridges which when energized periodically causes the recorder to record a check pulse equivalent to some pre-set weight -- this recording and a simultaneous time stamp provide a convenient check on instrument calibration.

After the prototype scale was constructed and installed, a short study was made of the dynamic weights of a number of trucks selected at random from the traffic stream. The results of the study were similar to those obtained in previous research, that is:

- (1) The electronic scale measures the applied load and its variation due to vehicle undulations during the short period of time that the wheel is on the platform (in this case about 0.05 sec. for a vehicle speed of 12.5 m.p.h.)
- (2) The positive and negative dynamic increments tend to cancel out so that practically the same total load is obtained for a given location whether the weighing is done statically or in motion.

The Swedish Road Board intends to continue its investigations into the collection of all types of vehicle data including in addition to weight and volume, the size and type of vehicle as deduced from the number and spacing of axles.

The scale described in this article seems to afford an efficient and relatively inexpensive way of collecting large amounts of wheel load data for research and design purposes.

Reference #24 is essentially the Swedish original of this article. Reference #47 is an operating manual for installing and using the scale and reference #66 is a research paper on the effects to be expected when the scale is installed on a cross-slope.

51. A Comparison of Methods Used for Measuring Variations in Loads Transferred through Vehicle Tires to the Road Surface. R. C. HOPKINS and H. H. BOSWELL. "Public Roads." Vo. 28, No. 10 P. 221. October 1957.

Variations in the weights-in-motion recorded by the Bureau of Public Roads electronic scale indicated that the vehicles were undulating as they crossed the scale. As these variations seem to follow a random pattern, it was thought that the scale was actually sampling the pressure applied through the tires to the road surface at random points in the vehicle's oscillation cycle. This was borne out by the fact that even though individual dynamic axle weights sometimes varied considerable from the static weights, a comparison of gross tonnages obtained by the two methods differed by only 2%.

This report describes an attempt to find the best way of measuring the amplitude and frequency of the dynamic loading cycle and to establish its correlation with the weight recordings of the electronic scale.

Three different methods were developed and tested during the course of this study. These were as follows:

- (1) Axle housing strain.

Two strain gages were mounted above and below the rear axle housing of the test vehicle. These four gages formed the arms of a resistance bridge circuit which detected changes in the axle housing strain due to changes in the wheel loads. This simple method worked best for a single wheel on a smooth surface at low speeds. Addition of the second wheel of a dual changed the lever arm of the cantilevered axle housing causing varying results depending on which wheel was supporting the greater part of the load. On rough surfaces at high

speeds, the unsprung load of the vehicle influenced the axle housing strains thus changing the previously determined calibration characteristics.

(2) Bulge of tire sidewalls.

Following the suggestions of previous researchers, the BPR developed an instrument to measure the change in tire sidewall bulge due to wheel load changes. The sidewall bulge was transferred through a system of rollers to a pair of steel straps. As the bulge caused the straps to bend, the change in strain was detected by strain gages attached to both sides of the straps. This change in strain was calibrated to known wheel loads and a curve plotted. Oscillograph recordings of the changes in strain as the vehicle moved along the road could then be translated into wheel loads applied to the surface. Many practical problems were encountered in the development of this method. Tire wobble picked up by the rollers affected the oscillograph pattern of the wheel load variations.

The roller placement on dual tires was very difficult.

(3) Changes in tire air pressure.

The most satisfactory method of measuring momentary changes in the dynamic wheel loads was by recording the changes in air pressure in the tire. Since the tire casing was distorted under load, a volume change and therefore an air pressure change would have to result.

A pressure pickup gage manufactured by the Consolidated Electrodynamics Corporation was connected by a small tube to a hole drilled in the valve stem of the tire tube. The diaphragm of the pickup gage was mounted so that its axis coincided with the axis of rotation of the truck wheel. The initial tire pressure was 55 P.S.I. - cold. Air pressure indications were transmitted electrically from the rotating wheel to the recording instruments in the truck bed through a system of slip rings. Calibration was accomplished by comparing the pressure pickup oscillogram with the recordings obtained by the other two methods. Static calibration was not possible because the indications transmitted by the slip rings were different for static and rotating situations.

The electronic scale used in the tests was located near Woodbridge, Va. This scale, embodying all the recommended improvements listed in Highway Research Board Bul. #50 was built by the BPR, the Virginia Highway Department, and an electronics manufacturer. The scale platform was seven feet wide in the direction of traffic and extended across the right hand lane of the two northbound lanes of U.S. Route #1.

Simultaneous weight recordings from all three detector types and the electronic scale were made during the test runs. Pneumatic detectors fore and aft of the scale platform actuated a radio signal as the truck passed over them. These signals were picked up by an antenna mounted on the truck and were recorded at the same time on the three detector oscillograms as pip marks. Since pips were also recorded at the same time on the electronic scale oscillogram, direct comparisons were possible.

Trial runs showed that the difference between static and dynamic weights and the amplitude of the changes recorded by the three detectors were too small for comparison purposes. The truck was therefore artificially oscillated at the natural frequency of the truck springs by a man jumping up and down on the truck bed. Definite peaks and valleys were then recorded on the oscillograms.

The following number of oscillation cycles were noted for the speeds shown during the time the truck wheel was on the seven foot scale platform:

Creep Speed	- 6 to 6 1/2 Cycles
10 MPH	- 1 to 1 1/2 Cycles
20 MPH	- 1/2 Cycle

Higher speeds would have required many trips across the scale to record a definite peak or valley, so no tests were run at speeds over 20 M.P.H.

Wheel loads as recorded by each of the three detector types were compared to those obtained from the electronic scale. Weights derived from axle housing strain and tire sidewall deflection were also compared. Correlation coefficients were computed for each combination. The correlation was good; thus showing that the electronic scale records the actual weight applied to the platform by a moving load with reasonable accuracy.

The natural frequency of oscillation of the truck moving over the open highway was found to vary from 2 1/2 to 4 cycles per second. Low frequency and high amplitude were noted for the rougher surfaces. Smooth surfaces resulted in higher frequencies.

The following conclusions were reached:

- (1) The best method of measuring the weight variations on the wheels of the vehicle is through the changes in tire air pressure.
- (2) Pavement deflections can be related to the actual dynamic loads.
- (3) Truck suspension systems can be compared for load transfer characteristics.
- (4) "Errors" of more than 5% previously charged to the electronic scale are probably caused by the undulating load of the moving vehicle.

53. Dynamic Forces Exerted by Moving Vehicles on a Road Surface. R.P.H.
BONSE and S. H. KUHN. Highway Research Board Bulletin #233. 1959.

The apparatus described in this paper was designed to measure both the horizontal and vertical forces applied to a point on the road surface by the wheel of a moving vehicle. The sensing element of the measuring system consists of a "stress recorder box" installed in a special manhole on the road center line. The detector consists of a circular stud, one square inch in area that may be adjusted vertically to lie flush with the road surface or to project slightly above it. The stud is connected in the interior of the box to a pair of flat springs which deflect when a load is applied to the stud. Deflection of the springs changes the spacing between a pair of condenser plates.

The resulting capacitance change is converted into an electrical signal which can be photographed on an oscilloscope screen. A similar set of condenser plates located near the top of the box measures the horizontal force applied to the stud as the vehicle wheel passes over it. Either longitudinal or transverse horizontal forces may be measured. The natural resonance of the spring systems of the device are about 500 C.P.S., much higher than frequencies induced by the passing vehicle (about 60 C.P.S. at 50 M.P.H.)

During the experiments conducted with the apparatus, nine influencing factors were varied, these were: wheel load, tire size, inflation pressure, vehicle speed, stud height above road surface, acceleration and deceleration, front and rear wheel, transverse (of the tire width) position of contact and type of tire tread. Oscilloscope recordings of the vertical force component showed the expected scatter due to variations in dynamic weight. In addition, the wave form was appreciably affected by the position of the stud relative to the center of the tire tread at the moment of passage. For positions near the center of the tread, the wave form was somewhat trapezoidal in shape, generally with two peaks of similar height; nearer the outside edges of the tread, the wave form was nearly a half sine wave.

The measured peak vertical force also varied with the position of the stud relative to the tread width; the higher values being obtained near the outside edges. This was attributed to the additional stiffness of the tire sidewalls.

Effect of some of the other variables on peak vertical loads were as follows:

- (1) Inflation pressure - increased peak load.
- (2) Vehicle speed - no significant effect.
- (3) Acceleration - increased load on rear wheels and decreased load on front wheels by an amount depending on the height of the center of gravity and the wheel base. Deceleration had a similar effect even though the dynamic load on the rear wheel decreased with deceleration. This anomaly was attributed to tire distortion under high torque.

Maximum vertical forces measured during the test runs varied as follows:

Inflation Pressure	Projection of stud above road surface	Range of Maximum Vertical Forces
28 ps.i.	None	30-44 psi.
" "	2.5. m.m.	100-155 psi.
" "	5.5. m.m.	155-240 psi.
70 ps.i.	None	70-88 psi.
" "	2.5. m.m.	210-24 psi.
" "	5.5. m.m.	400 psi.

Maximum vertical forces near the edge of the tread contact width averaged 15 to 24 psi. greater than those measured at tread center line for zero stud height.

55. Preliminary Analysis of Road Loading Mechanics. G. J. FABIAN, D. C. CLARK, and C. H. HUTCHINSON. Cornell Aeronautical Laboratory, Inc. Buffalo, New York. 1960

An intelligent approach to the solution of the dynamic weighing problem would require that something be known about basic loadiload loading mechanics in general and dynamic road loads in particular:

The cited article presents the preliminary findings on this subject by a research group under contract to the Bureau of Public Roads. The study is part of a comprehensive project investigating all phases of the highway life problem.

The road loading system is made up of two major parts; the vehicle and the road. These parts are interdependent as far as performance is concerned. Loads are applied to the road surface through the tire contact area, producing variations in deflection and stress. The loads include: the static weight of the vehicles, the variable forces transferred from the road profile to the vehicle and the loads transmitted to the road by the variations in tire elasticity induced by the vehicle's vibration.

The road profile represents the "as built" condition of the road as modified by time, traffic maintenance, and weather. This profile provides the "input" to the vehicle tire.

The vehicle applies loads to the road vertically through its suspension system, horizontally by acceleration and braking and laterally due to steering action, camber, and superelevation. Since the system is elastically supported, both the road input and the vehicle output are frequency dependent. Resonant frequencies could then occur, magnifying the loads transmitted through the tire contact area.

A literature survey provided the information needed to define typical road and vehicle sub-systems.

Previous studies had shown that static and dynamic road deflections of 0.03 inches and 0.05 inches, respectively could be tolerated without early surface breakup. The surface was regarded simply as a means of spreading out the loads eventually carried by the subgrade. Relative motion of the elastic road system was not considered in setting up the model. The road input to the vehicle tire was assumed to be a sine wave of fixed amplitude and frequency.

In establishing the vehicle model, the main concern was with the suspension system. The sprung mass (passengers, cargo, chassis and body) is supported on springs and shock absorbers which transfer the load through the unsprung mass (axles, wheels, steering system, etc.) to the tires. The tires support the load by deflection of the "air spring". Tire contact pressure is usually about equal to the inflation pressure. Tire damping of the vehicles' vibration was assumed to be negligible and was disregarded.

The weight of the unsprung mass on the rear tires was taken as about double that on the front tires. This weight averaged about 1000 lbs. on the front axle.

The most common type of suspension is the leaf spring. This spring usually has a constant of about 900 lbs. per inch on the front axle, 2000 lbs. per inch on the rear with full load static deflections of 4 1/2" and 3 1/2", respectively.

The leaf spring dampens the vehicles vibration frequency through static friction between the leaves. Since this damping is rather erratic, shock absorbers are used to provide a more reliable viscous damping. The usual critical damping ratio is about 20%. Leaf spring friction does not vary with loading.

The above characteristics were used in a mathematical vehicle model which could be used to predict system outputs in response to the "inputs" from the road profile. An analog computer was used.

In setting up the system model, it was found that considerable information was available concerning the vehicle sub-system and equations of motion could be evaluated. Defining the road sub-system was confined to considering only the static profile until further research enables a better understanding of the true conditions.

A heavy truck was chosen as the vehicle mode. Since the WASHO Road Test showed a 18,000 lb. single axle load to be critical for both rigid and flexible pavements, this loading was used in the model as the rear axle load. Front axle loading was considered as 9000 lbs. equally divided between 10 x 20 size tires. Gross-vehicle weight was therefore 27,000 lbs. Leaf springs were assumed on both axles. Shock absorbers were used on the front axle. Results were obtained considering the rear axle with and without viscous damping.

A typical road loading was derived from procedures developed by various authorities on pavement thickness design. As a first approximation an equivalent of 518 applications per day of a 1000 lb. wheel load was used.

The solutions yielded by the analog computer were the vertical forces transmitted by the vehicle in response to a given road profile and vehicle speed. These answers were expressed as ratios of peak dynamic load to static load. Since the tire print area increases with an increase in dynamic force, resultant pavement stresses are not proportionately greater under the increased loads. A load ratio of 4:1 increased the bending stress under the tire on a concrete pavement by about 3:1.

Only the "pitch" and "bounce" degrees of freedom were assumed for the model at steady-state speeds. Since the model was symmetrical about a longitudinal plane, only half the vehicle was used. Physical characteristics of the model were as follows:

Tires - 10 x 20 - singles on front, duals on rear
 Front spring constant - 900 lbs. per inch
 Rear Spring constant - 2000 lbs. per inch
 Front Unsprung Wt. - 500 lbs.
 Rear Unsprung Wt. - 1000 lbs.
 Front Sprung Load - 4000 lbs.

Rear Sprung Load - 8000mlbs.
 Wheel base - 144 ins.
 Center of Gravity - 96" back of front axle
 Tire Spring Rate - 4500 lbs. per inch per tire
 Interleaf Static Friction - 300 lbs. on front, 400 lbs. on rear
 Viscous damping (shock absorbers) - 20% critical.

The analysis performed by the analog computer involved the solution of six simultaneous equations to determine the vertical forces in the tire prints.

The problem was solved for two variations in the basic model; the unloaded truck weighing 8400 lbs. and the fully loaded truck with and without rear shock absorbers.

A harmonic analysis of six road profiles showed that the shape of the input wave representing road roughness was not as important as frequency. Sections of the road profile could be closely represented by a triangular, square or sinusoidal wave form. The sine wave was selected as giving the most realistic model response.

Since the model would respond with the same frequency to a number of different combinations of road wave lengths, much information could be obtained with just a few frequency responses. Input sine waves of 1/4, 1/2 and 3/4 inch total amplitudes were used.

Some of the more pertinent results of the analysis may be summarized as follows:

- (1) Vertical road loading forces - 3/4" amplitude and frequency of 10 C.P.S. for the loaded truck.
 - (a) Shock absorbers on all axles - Peak dynamic force under rear tires was 1.5 times static load.
 - (b) Without shock absorbers on rear tires - Peak dynamic force - 3 times static load.
 - (c) Unloaded truck without rear shock absorbers - Peak dynamic load - 7.5 times static load.
- (2) Curves were plotted for various input amplitudes with the ratio dynamic road load/static load as the ordinate and the ratio forward velocity/road wave length as the abscissa.

Some readings from these curves:

Input Amplitude	Shock Absorbers	Ratio-Forward Velocity Road Wave Length	Wheel & Load	Ratio-Peak Dynamic/Static
3/4"	no	1	Rear-Loaded	4+
1/4"	no	1	Rear-Loaded	3+
3/4"	yes	1	Front-Loaded	1.8
3/4"	yes	1	Rear-Loaded	1.5
1/2"	no	1/2	Rear-Unloaded	4.6
1/2"	yes	1/2	Front-Unloaded	2

The significance of these results seems to be that the dynamic wheel load can easily be double the static load even under very moderate conditions. The effect of shock absorbers is obvious. The unloaded vehicle responds with a much higher dynamic/static ratio than the loaded vehicle. This would not necessarily result in heavier road damage as the static loads are rather light.

The authors' conclusions were:

- (1) Dynamic road load may be significantly greater than static.
- (2) Size of the dynamic load depends on the dynamic properties of the vehicle and the road profile.
- (3) Shock absorbers reduce peak loading forces.
- (4) Pitch and bounce frequencies of unloaded vehicles are nearly resonant with human body frequencies. This results in riding discomfort.

Recommendations were:

- (1) Continuance of analytical model development with experimental verification.
- (2) Effect of tires on loading mechanics should be studied in detail.
- (3) The highway itself as a dynamic system should be investigated.
- (4) Highway life must be considered in dynamic terms.

References #58 and #65 report the results of further analyses by personnel at the Cornell Aeronautical Laboratory of the response of the roadway model to static and dynamic loadings. The analyses are general in scope and may provide a better insight into the dynamic weighing problem insofar as the response of the scale as a mechanical system is concerned.

60. Effect of Pavement Condition Upon Dynamic Vehicle Reactions. BAYARD
E. QUINN and D. R. THOMPSON. Purdue Research Foundation. Purdue
University, January 1962.

This study relates the interaction of pavement irregularities and the characteristics of the vehicle suspension system to the dynamic load applied to the pavement by the moving vehicle. The ratio of the force which a given vehicle exerts on the highway to the vertical displacement of the tire tread (F/X) may be obtained experimentally for various vibration frequencies. These data yield a curve which expresses the net effect of all the suspension characteristics of the vehicle. For a 1955 Chevrolet, for example, the F/X ratio showed peaks at 2 and 15 C.P.S. frequencies from 15 to 20 C.P.S. showed a steady decrease in the ratio. The range of frequencies from 1 to 20 cycles per second was thus determined to be critical. A pavement with surface irregularities that would induce vehicle vibrations within this range would therefore generate large dynamic loads between the vehicles' tires and the pavement.

The pavement condition is described in this paper by making a "power spectral density analysis". This statistical procedure makes use of the differences in elevation of the pavement surface at one foot intervals along

the path traveled by the vehicle. The arbitrary one foot spacing of the elevation measurements yields values which meet most of the requirements of randomness and is short enough to include all significant wave-lengths in the longitudinal undulations of the pavement surface. The highway "power spectrum" is expressed graphically by plotting the variations in elevations (in feet squared per cycle per foot of length) as the ordinates against the reciprocal of the wave length (in feet per cycle) as the abscissa. The area under the resulting curve between any two wave lengths then represents that portion of the total pavement roughness produced by this range of wave lengths.

To combine the highway power spectrum and the vehicle characteristics, it is necessary to introduce the factor of speed. This is done by multiplying the abscissae of the power spectrum curve by the speed and dividing the ordinates by the same value. The resulting curve is unique for the given speed and may be plotted with the aforementioned vehicle characteristic curve.

Final step in the analysis is the computation of the power spectrum of the dynamic force applied by the vehicle to the highway. When each of the variables is expressed as a function of frequency and certain conversions in units are made, the power spectrum of the dynamic force may be obtained by multiplying the pavement elevation power spectrum (for a given speed) by the square of the (F/X) function. If the dynamic force power spectrum is plotted for a given vehicle at a specified speed, the area under the curve represents the mean squared value of the force applied by the moving vehicle. When this procedure is repeated for various vehicle speeds and different types of roadway surfaces it is possible to plot a family of curves for one wheel of a given vehicle which show the variation in the root mean square value of the dynamic force with speed and pavement roughness.

The authors of this report checked the results obtained by their method through comparison with the dynamic load variation as measured by changes in tire air pressure for a test vehicle driven over a pavement of comparable roughness.

The conclusions reached through this study were:

- (1) Pavement conditions, vehicle suspension characteristics and speed influence the dynamic reaction between the vehicle and the highway.
- (2) The response of the vehicle suspension system as expressed by the (F/X) ratio tends to reach a maximum at certain critical frequencies.
- (3) When the "input" from road roughness or profile changes and vehicle speed cause the vehicle to vibrate at a critical frequency, maximum dynamic loads are produced.
- (4) At high speeds undulations in the pavement of long wave lengths may have the same effect on dynamic loading as short wave length irregularities at lower speeds.
- (5) To reduce the repeated impact loading of the pavement structure, it may be necessary to set up speed limits based on the suspension characteristics of various classes of vehicles.
- (6) There is a need to determine whether the large dynamic force due to high speeds is more or less detrimental than a small force at a lower speed.

References #54, #57 & #59 describe previous research in this field by Mr. Quinn and various co-researchers.

Recent Developments

Research and development in the field of dynamic weighing continue to be of interest to many governmental agencies and manufacturers. The present status of some of this work is summarized below.

MICHIGAN STATE HIGHWAY DEPARTMENT, PROJECT 52F-26.

Part A of this project, an experimental field test of devices to measure the length, width, height, weight, number and speed of passing vehicles, has been completed. The consultants, BPSCO Inc., have submitted a final report on Part A. Personnel of the MSHD Research Lab have begun work on Post Part A, an attempt to modify the weighing equipment to attain better accuracy. A complete description of the initial aims of the Michigan project may be found in reference #74, the Feasibility Study. This study also contains the mathematical justification for using the multiple scale system that has been extensively tested during the Michigan work.

NATIONAL COOPERATIVE HIGHWAY RESEARCH PROGRAM.

This organization is sponsoring a project that has as its objective the design of an in-motion weighing system to determine axle weights within $\pm 5\%$ of the true static weight. It is expected that some new principles may have to be developed to obtain this degree of accuracy.

GREAT BRITAIN.

Mr. J. J. Trott of the British Road Research Laboratory reported in July, 1963 that his agency plans to install 12 additional dynamic scales during the next two years. They are developing a "modular" scale two feet square and built of a light alloy that can be placed in the roadway as a single unit or in multiples transverse to the traffic flow. Advantages of this new type of platform are given as: higher rigidity, ease of placement and removal and the possibility of connecting the units either separately or in parallel to obtain wheel loads using different tracks on the road surface.

GERMANY.

Engineers of the Otto-Graf Institute in Stuttgart are developing a dynamic scale that can be installed in the roadway without the necessity of a large pit. This work is in line with the European trend toward the portable scale - an important factor when the primary purpose of the weighing is to obtain planning and research data.

KENTUCKY (KRF 3359, HPS 1 (22).)

Field testing of a four-load cell commercial scale and an experimental broken bridge type scale was completed in September, 1963. The testing program included variations in vehicle speed, amount of preload & method of applying preload. A random sample of trucks from the normal traffic stream on I-64 was also channeled across the two scales during the testing period.

Fabrication of a scale employing simply supported aluminum beams as the weight sensors is nearly complete. The scale will be installed in the pit formerly occupied by the four-load cell scale and a test program initiated. Results of the testing and an evaluation of the performance of each type of scale will appear in the project report for 1963. References #75 and #76 contain information about the effects of pre-loading the scale platform.

ADDENDUM

The following publications were received too late to include in the foregoing bibliography and are hereby added:

- 34.1 Final Report Part-A and Part-A (abridged) Automatic Weighing of Vehicles in Motion and Collection of Traffic Data. EPSCO INCORPORATED, MICHIGAN STATE HIGHWAY DEPARTMENT and BUREAU OF PUBLIC ROADS. October, 1963. (Received on April 15, 1964).
- 64.1 Untersuchung über die dynamischen Kräfte zwischen Rad und Fahrbahn und ihre Auswirkung auf die Beanspruchung der Strasse. (Investigations Concerning the Dynamic Forces Exerted between Wheel and Roadway and their Effect upon the Stresses Imposed on the Road.) DR.-ING. OTTO SVENSON, "Deutsche Kraftfahrtforschung und Strassenverkehrstechnik". Heft 130, 1959. 15 pp.
- 64.2 Wiegevorrichtungen für Kraftfahrzeuge und Anhänger. (Weighing Equipment for Motor Vehicles and Trailers). DIPL.-ING. HEINZ STRABER, "Deutsche Kraftfahrtforschung und Strassenverkehrstechnik". Heft 151, 1961. 48 pp.
- 64.3 Messungen der dynamischen Radlasten und Entwicklung eines Prüfhindernisses zur Feststellung Strabenschonender Fahrzeugbauweise. (The Measurement of the Dynamic Loads imposed upon Motor Vehicle Wheels and the Development of a Test Obstacle in order to discover a System of Vehicle Construction calculated to reduce the Stresses imposed upon the surface of the road). PROF. DR.-ING. P. KOEBLER, et al. "Deutsche Kraftfahrtforschung und Strassenverkehrstechnik". Heft 127, 1959. 42 pp.

APPENDIX B

INSTALLATION AND WATERPROOFING OF
STRAIN GAGES FOR THE BEAM TYPE SCALE



Laboratory Tests of Strain Gage Waterproofing Methods & Materials

The following was excerpted from the 1962 Annual Report:

A major problem in all previous attempts to develop a dependable dynamic scale has been the deterioration of the strain gages due to excess moisture. An investigation into the various methods and procedures for waterproofing strain gages has been made a part of this project as a corollary to the work on the beam type scale.

The Department of the Navy, at its David Taylor Model Basin in Washington, D. C. has done considerable research in this field. Mr. Mills Dean III of the Model Basin Staff prepared for this project an example of each of six different gage applications and waterproofing methods. The specimen gages (one type A-3 and one type AB-3, SR-4 gages in each sample) are mounted on a 9" x 12" x 3/4" aluminum plate and have shielded cables attached to permit periodic checks of gage resistance. The arrangement and numbering of the sample gages are shown in Figure 1. The plate was sandblasted and cleaned on both sides before gage application. Gages were cemented in place with HYSOL 0151. Waterproofing compounds used were as follows:

- (1) Gages 1 and 2 - Metal primed with PRC¹ 1531; gage covered with DLH² DI-JELL and PRC 1535 URETHANE. Edges were heat sealed.
- (2) Gages 3 and 4 - Same as (1) less primer.
- (3) Gages 5 and 6 - Same as (1) except PRC 1525 used as primer.
- (4) Gages 7 and 8 - Gages covered with DI-JELL, metal primed with EC³ B43.
- (5) Gages 9 and 10 - Same as (4) less primer.
- (6) Gages 11 and 12 - Gages covered with DI-JELL, metal primed with EC 853. All covered with CIBA⁴ epoxy.

The sample gages have been exposed to excess moisture conditions in the Civil Engineering Department's concrete curing facility since July, 1962. Systematic checks of the condition of the gages have been made. Gages 1 & 2 (~~and~~ above) have failed thus far (April 1964).

¹Products Research Corporation

²Baldwin Lima Hamilton Company

³Minnesota Mining and Manufacturing Company

⁴CIBA Products

B-2.

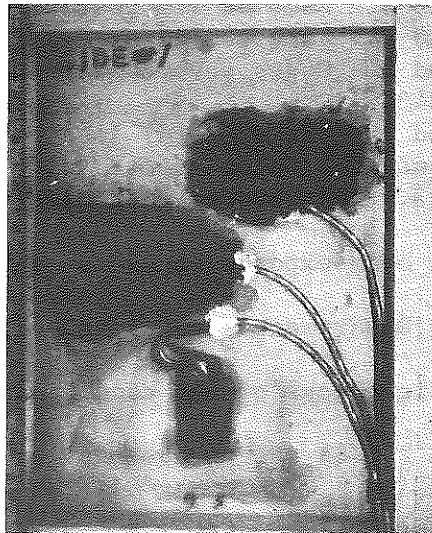
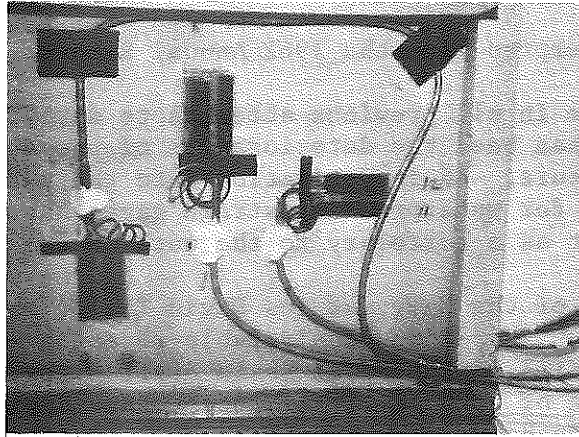


Figure 1. Arrangement of Sample Cages on Test Plate.

Installation of Strain Gages at David Taylor Model Basin

The following was excerpted from a memorandum to Professor David K.

Blythe from R. E. Puckett, dated September 13, 1963.

The two beams ~~had~~ been previously anodized. Both beams were cleaned with trichlorethelene before installing the gages. The SR-4 paper-backed gages which were purchased for the installation were not used. Instead technicians of the David Taylor Model Basin recommended the use of bakelite-backed gages. The reason for this was that the installation was to be used over a long period of time and for many strain repetitions. In addition, they supplied eight of the new semiconductor gages from their stock. Altogether they supplied eight each of the following gage types: B-L-H, AB-3, and B-L-H, AB-7; and four each of: B-L-H, SPB 3-18-12 and Micro Systems, PA 3-16-120 (the latter two are the semiconductor gages).

The gages were installed on the two beams, top and bottom, and as near the center line as could be gaged. Their arrangement on the beams is shown in Figure 2. The gages making up bridges #1 and #4 were wired into the bridge configuration on the beams. All other gages had their two external leads brought out through the waterproofing to permit external connections to each of the bridge arms. Specific wiring of all gages is also shown in Figure 1. Strain tests were made on bridge #4 (on the beam designated Beam II). The results of the static tests are given in Table 1.

Bridges #1 and #4 were designed for use in our testing program at the I-64 site. However, it was felt that additional elements should be provided to permit another pair of bridges to be available in case of failure of the first pair. The semiconductor gages were therefore placed in bridges #3 and #6. These gages have an upper strain limit of about 2000 microstrains. As was revealed in the static tests, they will not be useful in measuring heavy axle loads because the maximum strain induced in the beams by a 22,000 pound load was about 3500 microstrains (see Table 1). The major problem with the use of such gages is their extreme sensitivity. Practically no amplification of output signal is required.

TABLE 1.

STATIC STRAIN TESTS OF BEAM II

Increasing Loading			Decreasing Loading		
Load (Pounds)	Strain (micro-strains)	Difference	Load (pounds)	Strain (micro-strains)	Difference
0	10-1920		0	10-1905	
500	10-1990	70			
1,000	12-0070	80			
2,000	12-0230	160	2,000	12-0225	320
3,000	12-0392	162	3,000		
4,000	12-0550	158	4,000	12-0545	320
5,000	12-0710	160			
6,000	12-0875	165	6,000	12-0870	325
7,000	12-1030	155			
8,000	12-1185	155	8,000	12-1190	320
9,000	12-1350	165			
10,000	12-1510	160	10,000	12-1510	320
11,000	12-1670	160			
12,000	12-1830	160	12,000	12-1830	320
13,000	12-1980	150			
14,000	14-0140	160	14,000	14-0140	310
15,000	14-0300	160			
16,000	14-0455	155	16,000	14-0450	310
17,000	14-0615	160			
18,000	14-0775	160	18,000	14-0770	320
19,000	14-0935	160			
20,000	14-1095	160	20,000	14-1090	320
21,000	14-1250	155			
22,000	14-1410	160	22,000	14-1410	320
<u>Total:</u>					3505 micro-strains

Location of Gages:

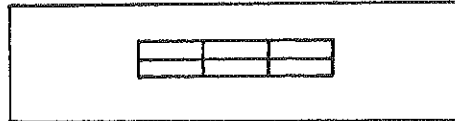
TOP (Compression)



BEAM I: 2 1 3

BEAM II: 5 4 6

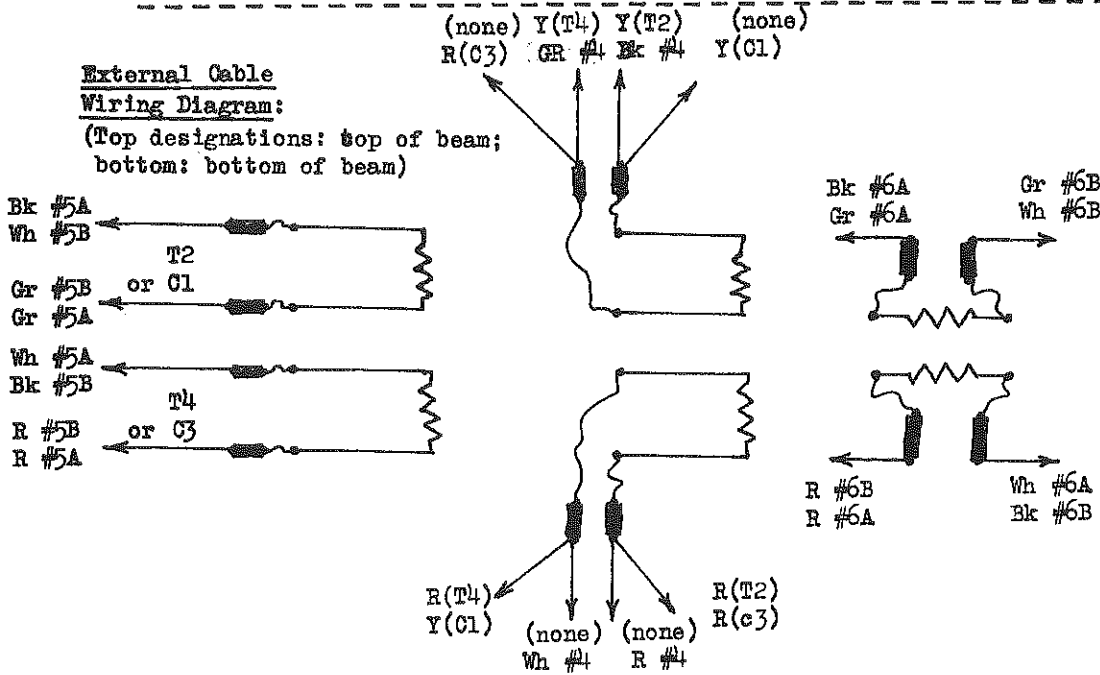
BOTTOM (Tension)



2 1 3

5 4 6

	Bridge No.	Gage Type	Bridge No.	Gage Type
	1	AB-3	4	AB-3
Beam I:	2	AB-7	Beam II: 5	AB-7
	3	PA 3-16-120	6	SPB 3-18-12



NOTE: Wiring for Beam I is similar, for bridges 1, 2, and 3 in lieu of 4, 5, and 6.

FIGURE 2



APPENDIX C

DATA COLLECTION INSTRUMENTATION



Data Collection Instrumentation

A console type, two channel Sanborn paper chart recorder was used at the U. K. Farm Test Site. Since the instrument shed was located only a few feet from the scale pit no additional signal amplification was necessary. The wiring arrangement for the two load cells of the Broken Bridge scale was similar to that described after herein for the same scale at the I-64 Test Site.

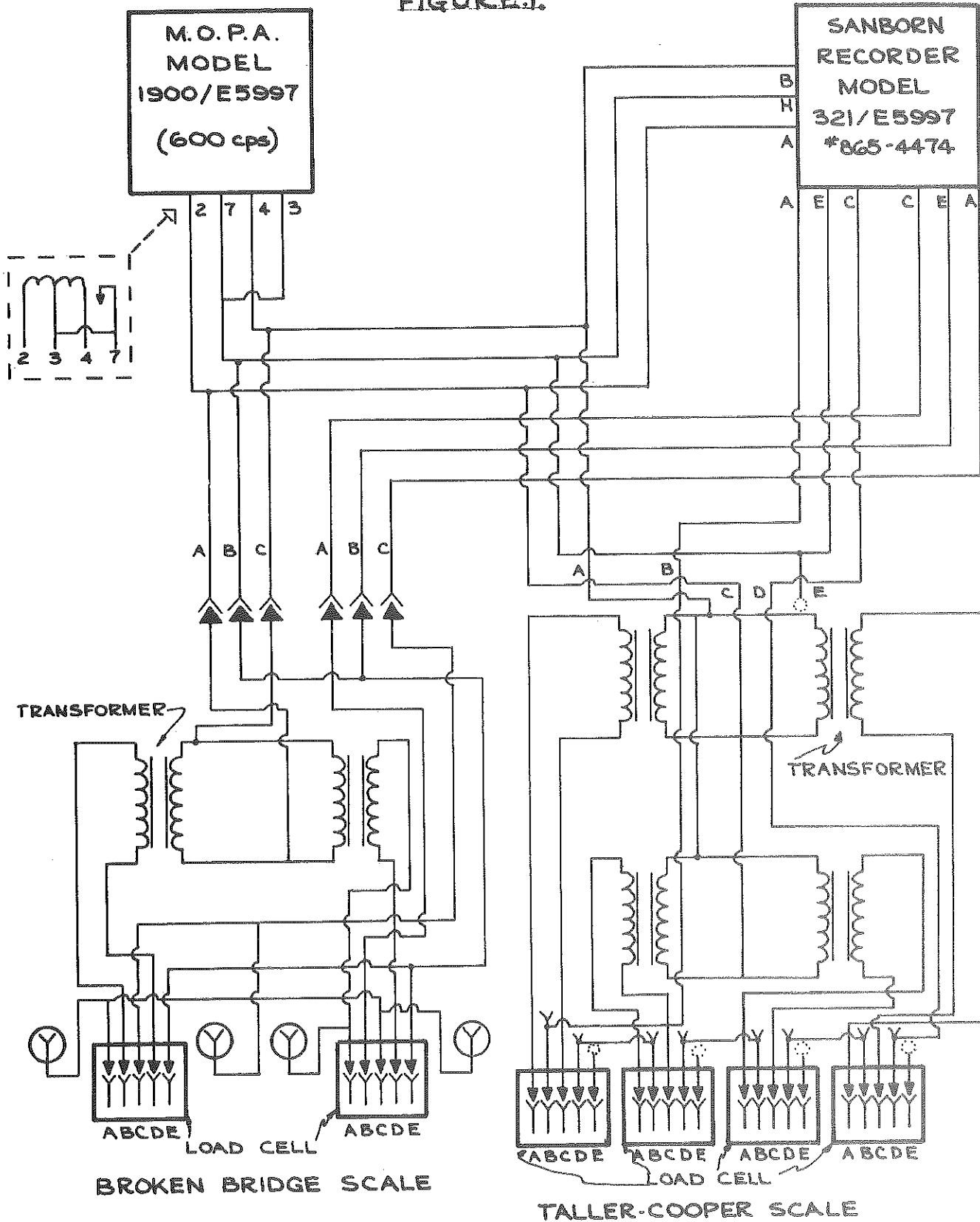
The following description of the instrumentation at the I-64 Test Site is taken from a report of the testing program conducted during the summer of 1963:

The Taller-Cooper platform uses four 20,000-pound load cells, and the broken bridge uses two 50,000-pound load cells. Each load cell is driven at its input by transformer coupling from a 600-cps master oscillator power amplifier (MOPA) that is common to all six of the transformers. The MOPA unit is installed at the static scale house with the analog recording equipment. About 600 feet of interconnecting cable is used between the pits containing the load cells and the scale house. The outputs of all load cells in each of the pits are added together electronically, so that the output of each platform will be directly proportional to any vertical load applied to the platform. In this way, the output from the scale will be a direct analog of the axle weights of passing vehicles.

The output signals from each scale are received in the static scale house, and, after necessary signal conditioning has occurred, the output signals are recorded on a 2-channel Sanborn Model 321 paper chart recorder. When the recorder has been calibrated, the recorded traces can be analyzed to determine several important quantities, including the weight of each axle of a passing vehicle, its speed, and its axle spacing. Because of the vast quantity of data that may be collected using this system, and the length of time that would be necessary to reduce and analyze the data, it was decided to use the digital computer for this purpose. The output data from the paper chart analogs were programmed for computer analysis. The computer output included the dynamic and static axle weights, average speed, axle spacing and the difference between dynamic and static weight in pounds and in percent.

A special electronic unit, a load-simulator calibration device, was designed and constructed for use at the test site. It permits calibration of the analog recorder in terms of weight units up to a maximum load of 20,000 pounds for each scale platform! The unit is useful only for the two platforms at the I-64 site, but because of its operating characteristics, it may be altered to fit the requirements of other platform configurations. The load simulator consists of a pair of voltage-divider networks, each fed by the MOPA through a transformer. In this way, the same voltage that is used to excite the load cells is also used as a reference for the simulator. The voltage division ratios for the divider networks are set at an output of 2 mv/volt for the Taller-Cooper scale, and at an output of 0.8 mv/volt for the Broken Bridge scale. These outputs correspond to the actual outputs expected from each of the scales, when a load of 20,000 pounds is applied to them. Thus, the maximum output from the simulator network represents a simulated load of 20,000 pounds. Each of the divider networks is designed to have a constant output impedance of 1,000 ohms at all values of simulated loads, from zero to the maximum of 20,000 pounds. The unit can be used to simulate loads up to the maximum, in incremental steps of 1,000 pounds. Schematic wiring diagrams for the scale installations at the I-64 Test Site are shown in Figure 1.

**WEIGHING SYSTEM WIRING DIAGRAM
FIGURE J.**





APPENDIX D

THEORETICAL CONSIDERATIONS



The following is excerpted from: "COMPARISON OF TWO METHODS FOR PRELOADING ELECTRONIC SCALES" by Russell E. Puckett, Assistant Professor of Electrical Engineering and James E. Gover, Research Assistant in Instrumentation, University of Kentucky.

To record dynamic load data, some means must be provided for detecting the load. A transducer capable of accepting the load data as a mechanical force and converting it to an electrical analog may be used in an electronic weighing system. The input to an electronic scale is a physical force proportional to the applied load. The output of the transducer should be an electric analog of the load. Many types of load detectors have been used but the strain gage load cell has been employed in the research reported here.

Commercial designs have been developed for electronic weighing systems that use a platform supported at its four corners by load cells; figure 1 shows a typical installation. The platform is set level with the road surface to measure the axle loads of trucks as they roll over it. The output of the load cells is proportional to the weight applied to the platform by the truck wheels. Many problems have been encountered when this type of system has been used to measure the axle loads of trucks in motion. The principal problem has been related to leveling the platform on its four supports so as to prevent its tipping and thus causing unbalanced loads on the four load cells. Some degree of success has been obtained in overcoming this problem. By preloading the platform with tension turnbuckles and steel rods, it has been leveled and the tendency for it to oscillate upon application of load has been greatly reduced.

To eliminate horizontal movement of the weighing platform without reducing the sensitivity of the system to vertical loads, the Research Organization for Roadbuilding in West Germany developed and built a broken-bridge design that is less subject to vibration than the platforms supported on four corners. The broken-bridge design is shown in figure 2; this system has two, narrow steel boxes that rest on the foundation of the platform's supporting structure. Load cells that convert the load into an electric analog are located beneath the center joint connecting the halves of the bridge.

A broken-bridge platform, based on the German design, was developed for the research project at the University of Kentucky and installed on the University's farm for use in different tests of the electronic weighing system. Two types of preloading devices - steel rods and turnbuckles or heavy coil springs - were attached to the platform to stabilize the system to the applications of dynamic loads. Tests were made to determine the performance of the system with each of the preloads.

Both preloading methods reduced platform oscillation under loading. However, the overall sensitivity of the recording instrumentation was reduced more when the steel rods were used for preloading than

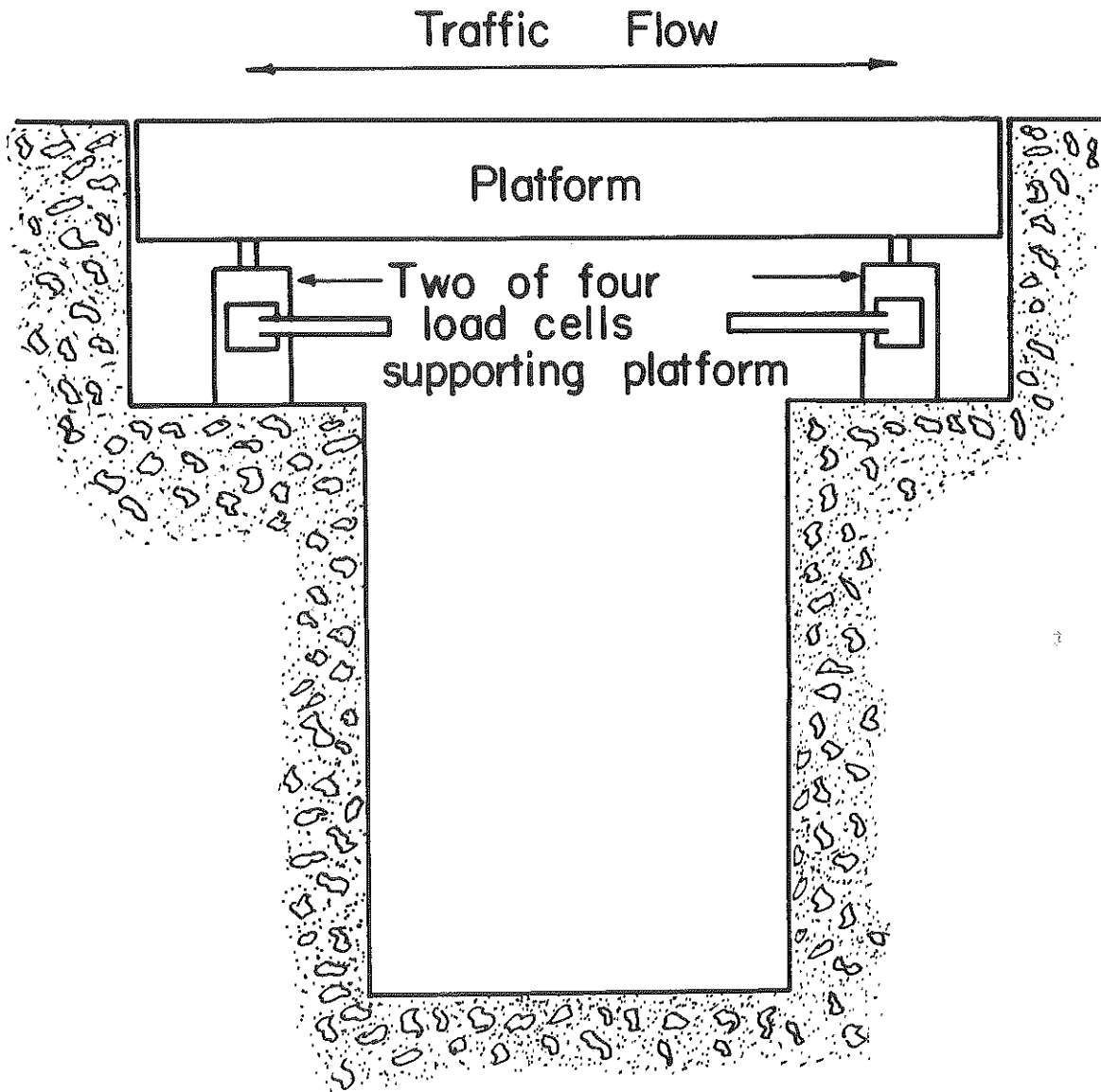


Figure 2. Installation of Broken Bridge Platform.

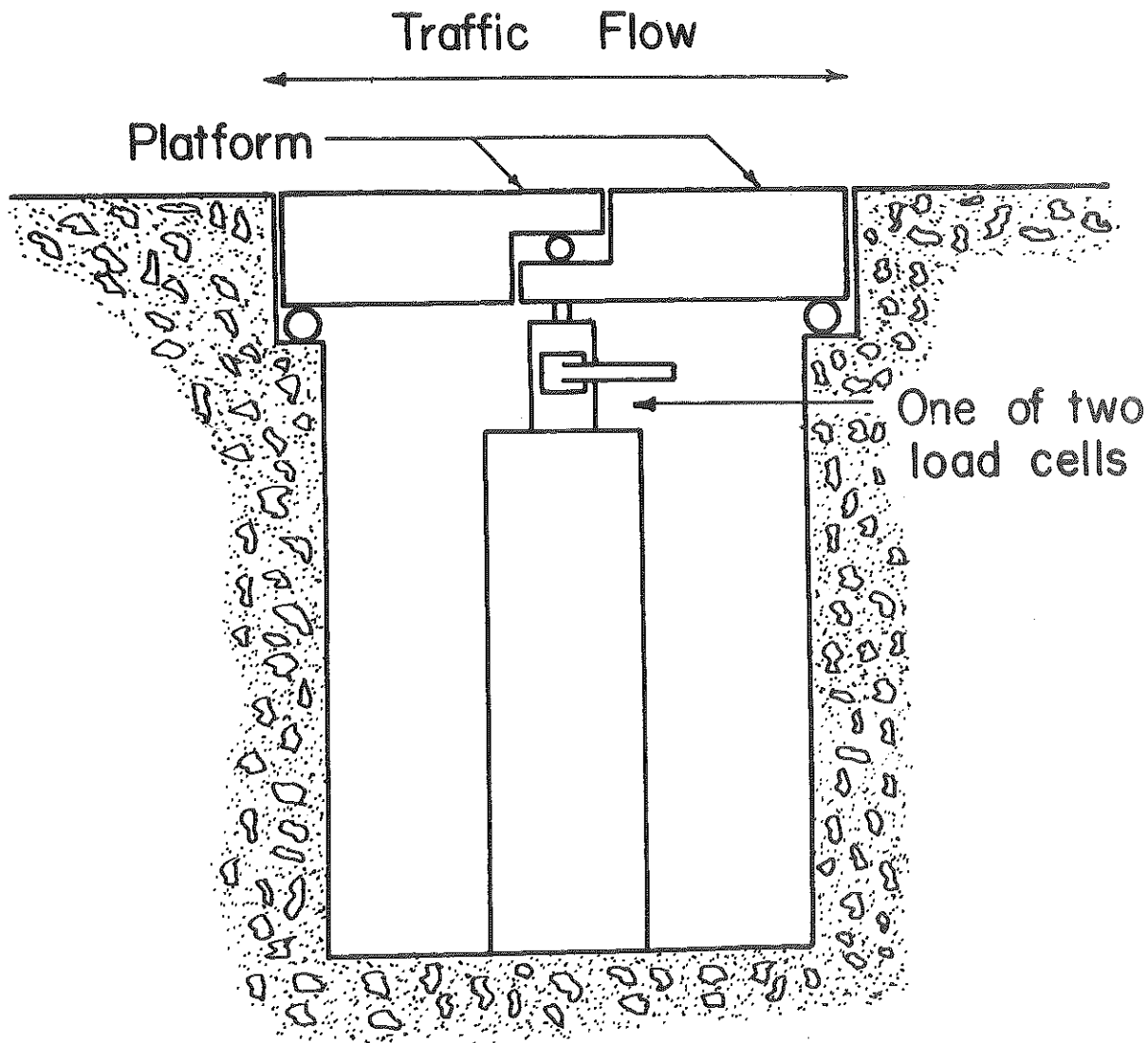


Figure 1. Installation of Platform Supported at Four Points.

when the coil springs were used. The output of the load cells supporting the platform was greatly reduced when preloading was accomplished by the steel rods but the output remained practically at its "no-preload" value for any load when the springs were used for preloading the system. The two preloading methods and an analysis of the differences in sensitivity of the system are discussed in detail in the following paragraphs.

The force diagram of figure 3 represents the broken-bridge weighing platform. P_0 represents the preload applied to the platform by each of the two preloading members, one at each end of the platform. For this analysis it was assumed that no bending of the platform occurs between the load cells and the points of application of the preload. It was also assumed that a linear relationship of the preloading members exists between their elongation and the force applied. Based on these assumptions, the preload was presented by the expression:

$$P_0 = ky_0 \quad (1)$$

Where,

P_0 = preload
 y_0 = elongation of preloading members
 k = constant of proportionality

Figure 4 is a force diagram of the platform as it appears when an axle load of $2W$ was applied symmetrically to the platform. Such an application causes compression of the load cells to some distance Δy . Application of the axle load to the platform reduced the tensile force in each of the preloading members by $k\Delta y$. Summation of the vertical forces on the platform showed that the load carried by each load cell may be expressed as:

$$P_1 = P_0 - k\Delta y + W \quad (2)$$

Where,

P_1 = load on load cell
 P_0 = preload
 k = constant of proportionality
 Δy = distance load cells compressed
 W = applied weight (actual load)

When the preload was first applied, the instrumentation was adjusted to its zero position. When an axle load was applied to the platform, the instrumentation indicated an analog of the difference between the initial preload value and the load carried by the load cell. This difference is the value of $P_1 - P_0$ which may be expressed in terms of the distance of compression of the load cell, equation (2), as:

$$P_1 - P_0 = W - k\Delta y \quad (3)$$

Equation (3) shows that the analog of the weight indicated on the instrumentation will be in error by $k\Delta y$. Therefore, this factor should be kept as small as possible so that the analog of the applied load will be more nearly representative of the actual load, W . The magnitude of Δy is pre-determined by the size of the load applied to the platform and the basic

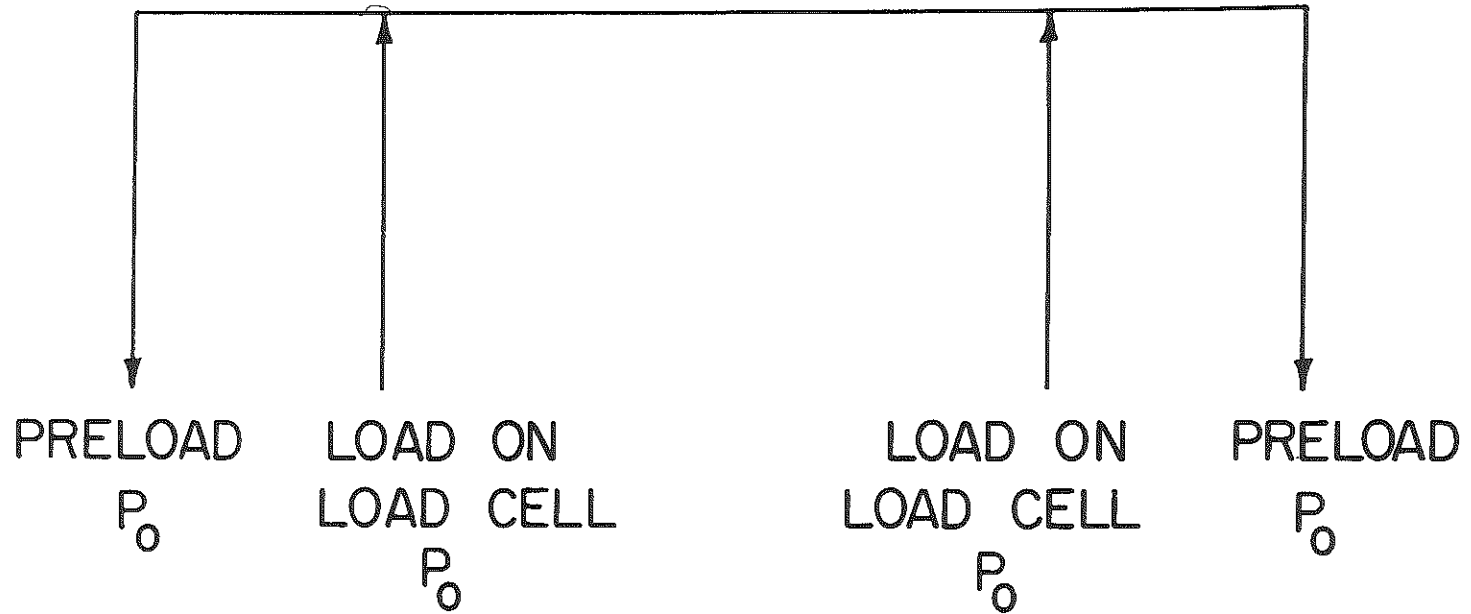


Figure 3. Force Diagram - Platform with Initial Preload - No Applied Load.

D-6.

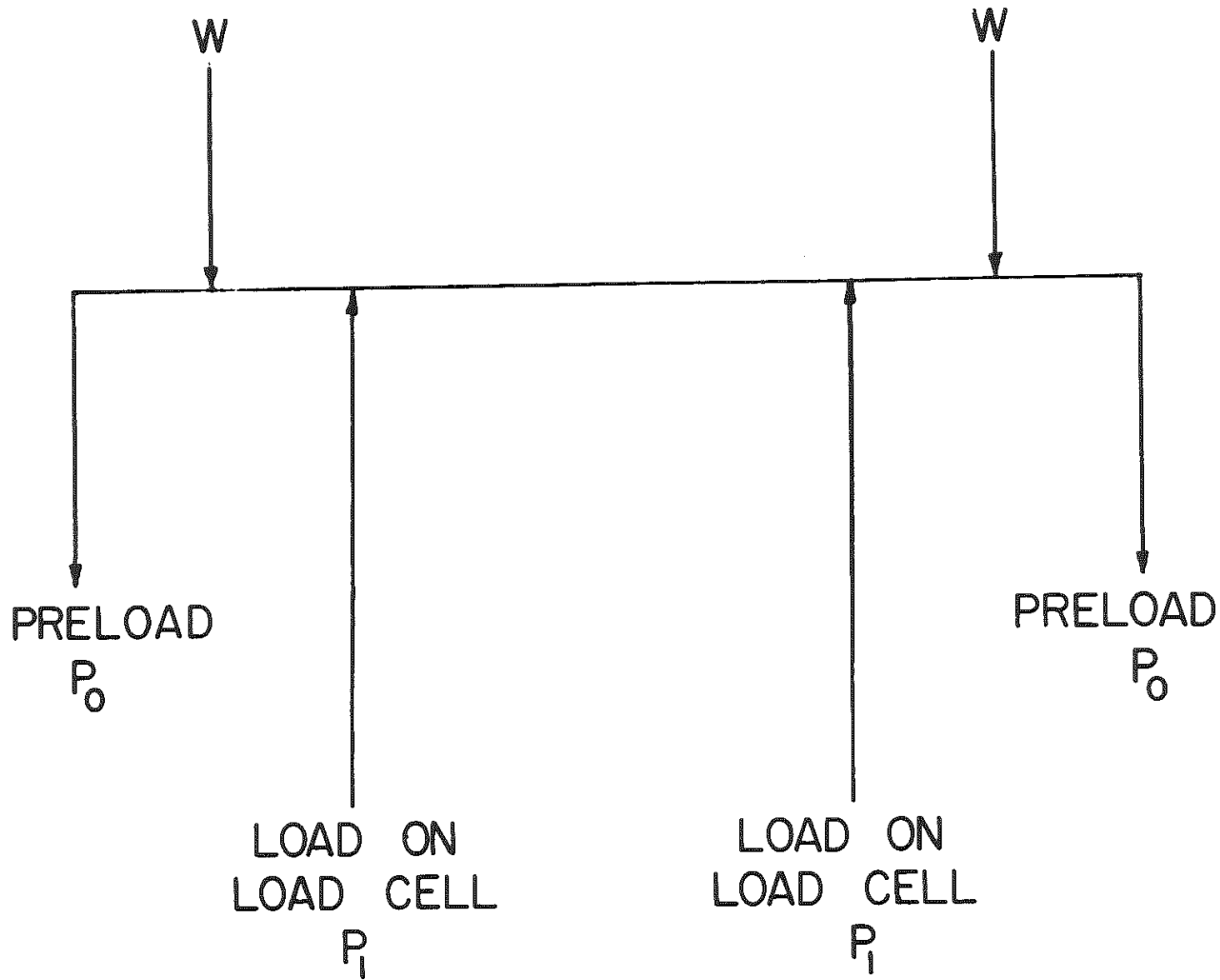


Figure 4. Force Diagram - Preloaded Platform with Applied Load.

sensitivity of the load cell. For the type of load cell used on this project, Δy was approximately 0.010 inch for a 50,000-pound load. This shows that changes in the value of k are required to increase the overall sensitivity of the system.

Because the initial preload equals ky_0 , the value of k must not be made so small that the product ky_0 is too small to permit completion of the original purpose of preloading the platform - stabilization of the platform and reduction of vertical oscillation. This requirement suggests use of a device that will show a large value for y_0 and a small value for k , thereby keeping $k\Delta y$ small, as the product.

Preloading during these tests was achieved in two ways: (1) heavy springs were mounted between the platform and the bottom of the scale pit, and (2) steel rods were tied to the platform and anchored to the bottom of the scale pit. Both devices were adjustable to permit changing the value of preload. Because of the physical construction of the pit and the platform, both the steel rods and the coil springs were limited in length.

An extension of equation (2) shows the effect of the factor $k\Delta y$ in the two methods of preload. Using equation (1), the effect of the factor may be written as:

$$P_1 = ky_0 - k\Delta y + W \quad (4)$$

or as:

$$P_1 = k(y_0 - \Delta y) + W \quad (4)$$

When the coil springs were used for preloading, the initial elongation of the preload member could be made large in comparison with any compression distance during the application of a load, and can be expressed as:

$$y_0 \gg y \quad (5)$$

A "worst case" check may be made for equation (5). Assume that the springs are preloaded at an elongation of 6 inches and that a 25,000-pound axle load is applied to the platform. If the load were placed symmetrically on the platform supported by two load cells, each capable of being compressed 0.010 inch at 50,000-pound load, the compression distance of a cell would be:

$$\Delta y = \frac{12,500}{50,000} \times 0.010 \text{ inch} = 0.0025 \text{ inch.}$$

Because y_0 equals 6 inches, equation (5) is valid.

When preloading is accomplished by using coil springs, equation (5) may be approximated as:

$$y_0 - \Delta y \approx y_0 \quad (6)$$

Based on this approximation, equation (4) may be stated as one or the other of the three following expressions.

$$\begin{aligned} P_1 &= ky_0 + W, \\ P_1 &= P_0 + W, \\ P_1 - P_0 &= W. \end{aligned}$$

Thus, when coil springs are used for preloading, the applied load can be recorded as an electronic analog that has no serious error caused by the preload. However, when steel rods are used for preloading the platform, the approximation developed in equation (6) is not valid because the characteristics of steel rods prevent their stretching any significant distance. Consideration of equation (4) shows that when steel rods are used for preloading significant error will be reflected in the analog for any load applied to the platform.

Further manipulation of equation (3) simplifies the comparison of the two methods of preload tested. The load carried by the load cell may be written as:

$$P_1 - P_0 = C \Delta y \quad (7)$$

Where,

C = basic sensitivity of the load cell.

Substitution of equation (7) in equation (3) yields either

$$P_1 - P_0 = W - k \frac{P_1 + P_0}{C}$$

or

$$(P_1 - P_0) = \frac{W}{1 + \frac{k}{C}} \quad (8)$$

Equation (8) is illustrated in figure 5. The slope of the line defining actual sensitivity is:

$$\frac{1}{1 + \frac{k}{C}}$$

compared with the maximum possible slope of unity when no preload is being used or when $k = 0$.

Equation (8) indicates that the overall sensitivity of the measuring system is reduced by any preload, and the sensitivity depends only upon the method of application of the preload; that is, the value of k. The difference between the load applied and its analog, when no preload was used, is given by the separation of the straight line in figure 5. Because the lines are straight, any error of an analog of load will be a fixed percentage of the load it represents, regardless of the magnitude of the load. Also, the error will be dependent upon the magnitude of the preload being used. This reduction of the system's sensitivity will be a constant, provided the value of k remains constant.

The graph of figure 5 has been plotted for only one value each for k and C. Other values would, of course, yield different curves. The separation of the two lines would increase for larger values of k. This again emphasizes the necessity for keeping the value of k as small as possible; the separation represents the reduction of the overall sensitivity of the instrumentation system.

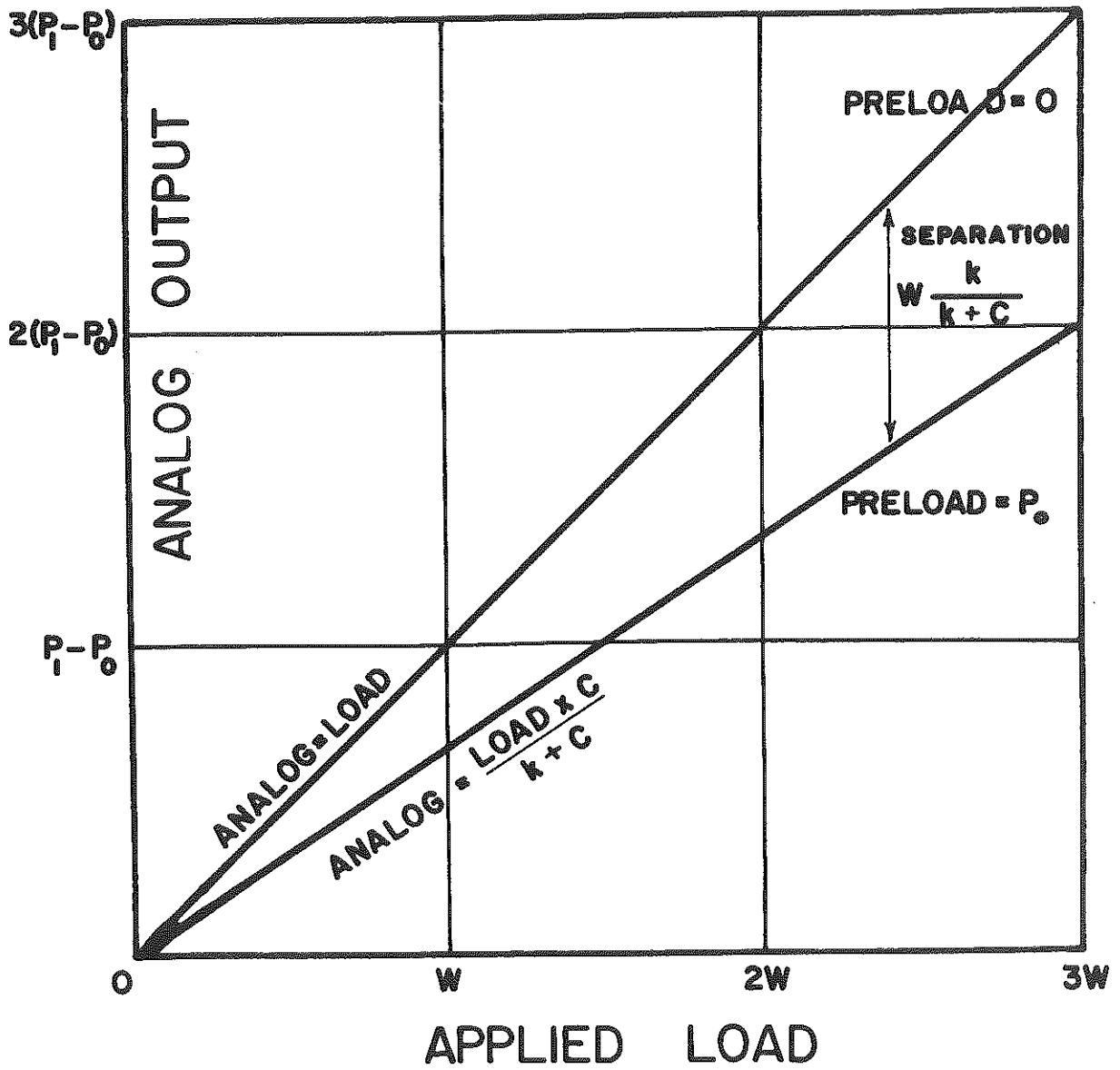


Figure 5. Theoretical Analog Output As A Function of Applied Load - Constant Preload.

In order to check the validity of the foregoing analysis of preload methods, a 3-axle truck was used for controlled tests. The amount of preload was based on the static weight of the front axle of this truck. The preload - either coil springs or steel rods - was applied to the platform in increments of 50 percent of the static weight. Weights were recorded at different speeds of the truck and for various amount of pre-load that ranged up to 200 percent of the front-axle weight. Typical results for each of the 3 axles obtained from these tests are shown by figure 6.

Lines representing the theoretical sensitivity curves of the system have been included in figure 6 for comparison with the results of the experimental tests. Although the experimental curves do not coincide with the theoretical predictions, they have the same general trend in slope. Part of the difference in the curves has been attributed to some bending of the platform between the load-cell supports and the point at which the preload was applied to the platform. Other factors, such as changes in the value of k of the preload devices and inaccurate measurement of the preload being used, also may have accounted for some of the difference between the curves. The curves for preloading with springs and those for preloading with steel rods have different slopes: this difference shows the effect of the different values of k .

From an analysis of the two methods of preloading the platform of an electronic weighing device with coil springs and with steel rods, it has been concluded that preloading with coil springs affords better stability and has little effect on the sensitivity of the measuring system.

To achieve maximum benefit from an electronic weighing system, the largest possible output must be obtained. The output analog of the applied load always will be relatively small and anything that reduces or tends to reduce it would be avoided or made as ineffective as possible.

The research demonstrated that heavy coil springs, which may be stretched a considerable distance in relation to motion of the weighing platform, afforded stability of the platform while maintaining the overall sensitivity of the measuring system. When steel rods were used for preloading however, the sensitivity of the system was reduced to an extent that negated the effectiveness of the rods in stabilizing the platform. Therefore preloading a dynamic platform with coild springs is more advantageous than using steel rods for this purpose.

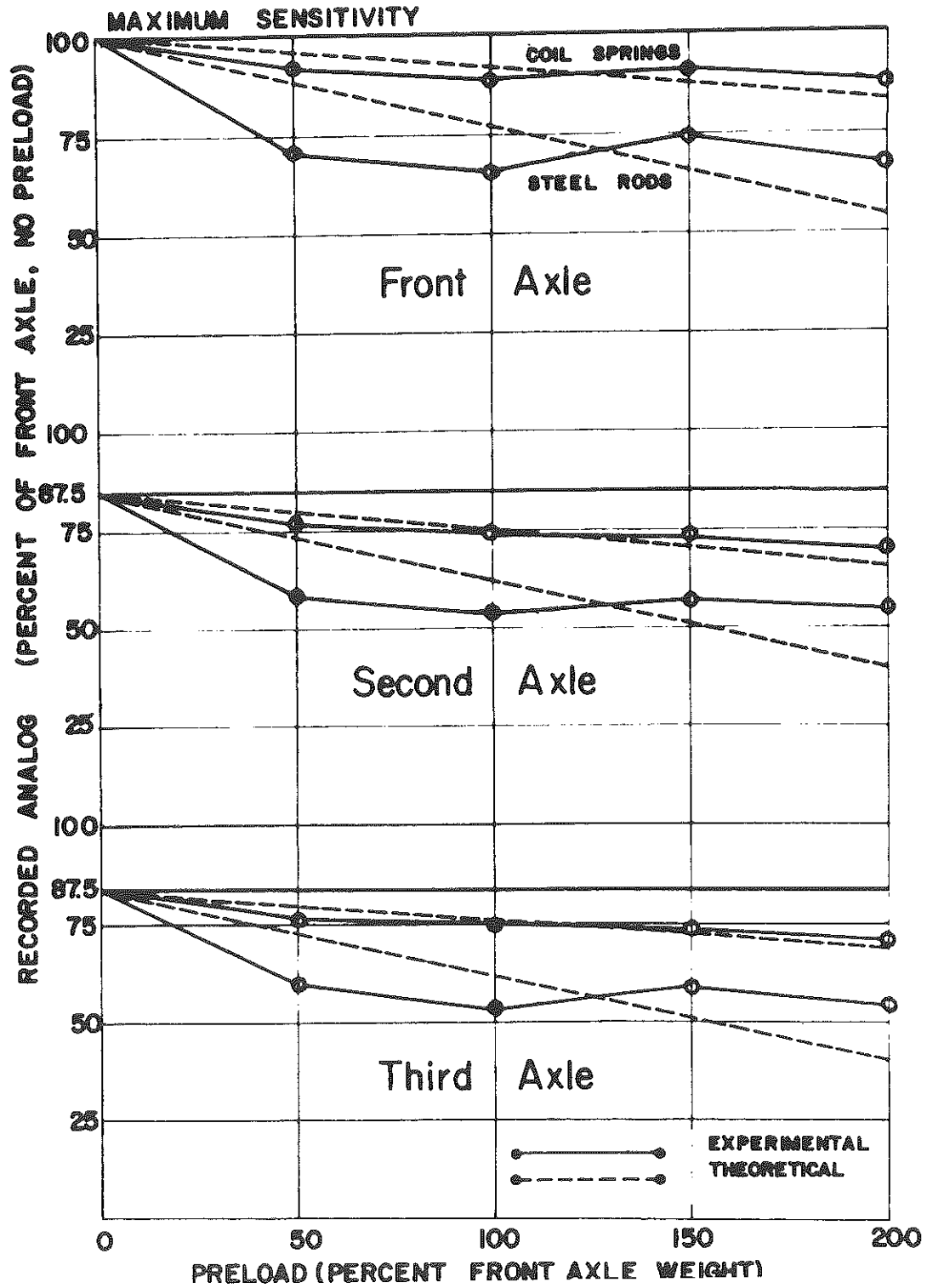


Figure 6. Experimental Results Showing Reduction in Sensitivity Caused by Preload.

The following is excerpted from: "A DESCRIPTION AND ANALYSIS OF THE BROKEN BRIDGE TYPE ELECTRONIC SCALE" by Charles C. Schimpeler, Graduate Student in Civil Engineering, University of Kentucky, 1962.

In an analysis of a dynamic weighing system, it becomes apparent that the problem of vibration must be considered. Several approaches to the solution of the problem follow.

1. Checking the Dynamic Response of a Bridge Unit

Due to the inertia of the weighing platform and the rapid application of the load, it is possible that the load cell will not receive the true load. The following discussion is designed to show that the inertia of the platform will not have a significant effect on the weight recorded by the scale, or, in other words, the dynamic and static response of the scale will be equal. For a given load function F (represented in Figure 3-1) and a given weighing system (Figure 3-2) the deflection at the load cell is to be determined. The general equation of motion for the system is $T = I \alpha (l)$

Where $T =$ Torque

$I =$ Mass moment of Inertia of approximately 1/2 bridge unit of about point 0.

$\alpha =$ angular acceleration

$k =$ spring constant of load cell $= 5 \times 10^6$ lbs/in

$x =$ distance from rocker support

$\delta =$ deflection at load cell (spring)

$\theta =$ angular displacement of bridge unit pivoting about rocker supports

$i =$ any specific time interval

$l =$ width of 1/2 bridge unit in direction of travel

$$F \cdot x - k\delta = I \frac{d^2\theta}{dt^2} \quad (3-2)$$

$$\delta = \theta l \quad (3-3)$$

$$F \cdot x - k\theta l^2 = I \frac{d^2\theta}{dt^2} \quad (3-4)$$

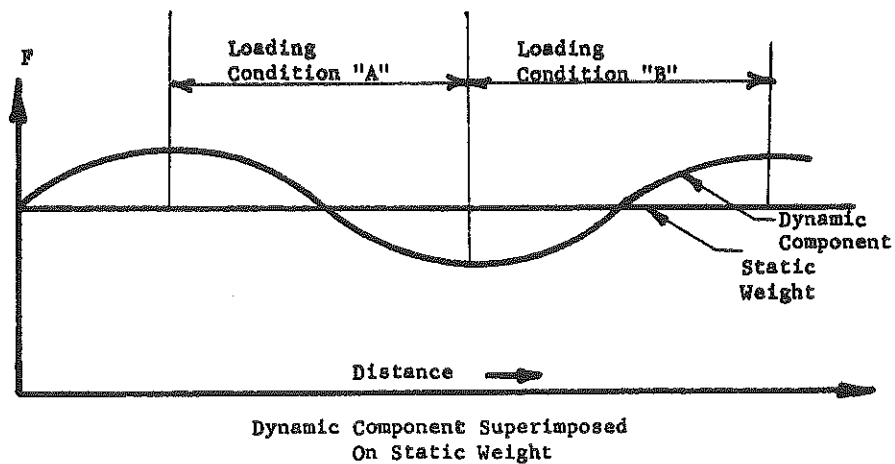


Figure 3-1

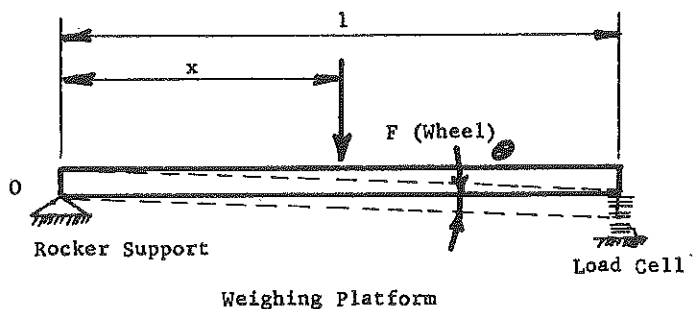


Figure 3-2

The solution of the differential equation is accomplished by the use of difference equations (numerical methods) and the backward difference operator. Thus:

$$F \cdot x - k\theta^2 = \frac{I}{\Delta t^2} (\theta_i - 2\theta_{i-1} + \theta_{i-2}) \quad (3-5)$$

As can be seen from the forcing function (the actual force being applied to the road surface at any time, Figure 3-1) the load on the scale is composed of the static weight of the vehicle and a dynamic component which may be positive or negative. The vertical acceleration of the vehicle caused by the undulation of the cargo on its springs creates the dynamic component. The dynamic component will be positive when the vehicle is accelerating upward or relieving the compressed springs.

From the time scale on the load diagram (established by knowing recording chart speed and vehicle speed) the load at any time was determined: The trace produced by an accelerometer mounted in the loaded truck was matched with the trace produced by the electronic scale load cell output to obtain the dynamic component of the load. This component ($F = ma$), was added algebraically to the known static weight. The dynamic weight obtained agreed with that recorded by the scale. Equation 3-5 (results in left side of Table 3-1) shows that theoretically the two should agree.

For the purpose of solving Equation 3-5 ten time intervals or eleven distance intervals were established; the reason for using one more distance interval than time interval was that the assumption $t = 0$ at the first distance x out on the scale makes necessary one distance interval before time starts (see Table 3-1). Using the initial conditions, $x = \lambda/11$, $\theta_i = 0$, $\theta_{i-1} = 0$ at time $t = 0$ the equation can be solved by numerical methods. The solution progresses step by step across the beam until the desired result, θ_{11} is found.

A typical solution using the backward difference operator will be shown. The original assumption made is that $\theta_1 = 0$, so the first step will not be considered. At position 2 the equation will be:

$$F \cdot x - k\theta_2^2 = \frac{I}{\Delta t^2} (\theta_2 - 2\theta_1 + \theta_0) \quad (3-6)$$

The equation yields $\theta_2 = 0.000107$ radians. Knowing θ_2 and θ_1 , θ_3 can now be calculated. From a recorded load curve similar to that shown in Figure 3-1, the value $F_2 = 7080$, the distance $x = 0.364$ and the time $t = 0.00416$ may be read.

Using the value of θ computed above, it can be said that $\delta = \theta \lambda$ and $F = \delta k = k\theta \lambda$. (3-7) & (3-8)

Therefore the force in the spring (load cell) can be calculated. The static values were computed by summing moments about the pinned end.

TABLE 3-1
 STATIC=DYNAMIC RESPONSE COMPARISON (1)

Position i	SPRING FORCE Max-Min (Condition A)		SPRING FORCE Min-Max (Condition B)	
	STATIC	DYNAMIC	STATIC	DYNAMIC
0	0	0	0	0
1	656-	0	540	0
2	1290	1260	1115	1110
3	1900	1900	1710	1710
4	2480	2480	2320	2320
5	3060	3000	2940	2930
6	3600	3600	3600	3600
7	4130	4130	4280	4270
8	4630	4630	4980	4970
9	5110	5120	5700	5700
10	5560	5560	6440	6430
11	6000	6000	7200	7200

(1) For loading conditions see Figure 3-2

(2) 0 1 2 3 4 5 6 7 8 9 10 11

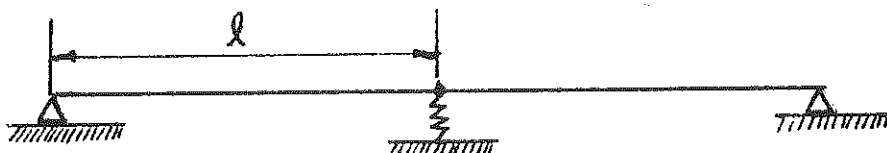
Positions of load for above calculations

Since the total length of the scale in the direction of traffic is only four and one-half feet, it is not possible for a complete loading cycle to occur while the axle is on the platform. Two different parts of the cycle were therefore considered. The first was the loading condition obtained by placing the beginning of a decrease in the dynamic component at the time $t = 0$. The second was the opposite condition or the beginning of the increasing half of the dynamic cycle at time $t = 0$. Results obtained for each of the ten time intervals are shown in Table 3-1. As can be seen, the theoretical dynamic weight transferred to the load cell by a load moving slowly across the bridge unit is exactly the same as that determined by static moment equations. Therefore, it can be concluded that the inertia of the bridge unit does not retard the transfer of load through the platform to the load cell.

2. Checking for Resonance

The second analysis consisted of determining if a resonant condition can be approached under the existing combination of the applied frequency and the natural frequency of the weighing system. Resonance is a vibration situation caused by an applied frequency which approaches or equals the natural frequency of the vibration system being considered; in this case, the electronic scale. When resonance does occur, extreme magnification of the dynamic component results. Analogies to equivalent vibrations system may be illustrated by the following examples.

The first equivalent system (Figure 3-3) may be simulated by two rigid bars, pinned at one end and supported at the other by a coil spring (load cell).



Equivalent Vibration System No. 1.

Figure 3-3

From the static deflected position, the differential equation of motion for the system shown is:

$$K_2 (\bullet l) l + -2I \frac{d^2\theta}{dt^2} \quad (3-9)$$

$$\frac{d^2\theta}{dt^2} + \frac{K_2 l^2}{2I_0} = 0 \quad (3-10)$$

The solution of this equation for the frequency of vibration is:

$$f_n = \frac{l}{2\pi} \left(\frac{K_2 l^2}{2I_0} \right)^{1/2} \quad (3-11)$$

Where θ = Angular displacement of the platform in radians

l = length of one platform = 2'0"

K_2 = Spring constant of load cell = 5×10^6 lb./in.

I_0 = Mass moment of Inertia of half of one platform about point 0 = 9896 lbs. - ft. - sec²

Note:
$$f_n = \frac{1}{2\pi} \left(\frac{K_2 l^2}{2I_0} \right)^{1/2}$$

$$f_n = \frac{1}{2\pi} \left(\frac{5 \times 10^6 \times 12 \times 4}{2 \times 9896} \right)^{1/2}$$

= 175 cps. The natural frequency of the scale platform.

The second equivalent vibration system (see Figure 3-4) may be represented as a simply supported beam. In this system the load cell is assumed to be rigid or nondeflecting. The part of the platform which resists moment is the channel section over the load cell and the dead load is equal to one half the weight of the bridge unit. The formula

$$f_n = \frac{n^2 \pi}{2} \left(\frac{2EI}{Wl^4} \right)^{1/2} \quad (3-13)$$

Describes the natural frequency of the system.

$$n = 1$$

$$g =$$

$$g = 32.2 \text{ ft/sec}^2$$

$$E = 30 \times 10^6 \text{ psi}$$

$$I = 312.6 \text{ in}^4 = \text{moment of inertia of area of section subjected to bending (one channel)}$$

$$W = 38.4 \text{ lb./in.}$$

Using these values in Equation 3-13:

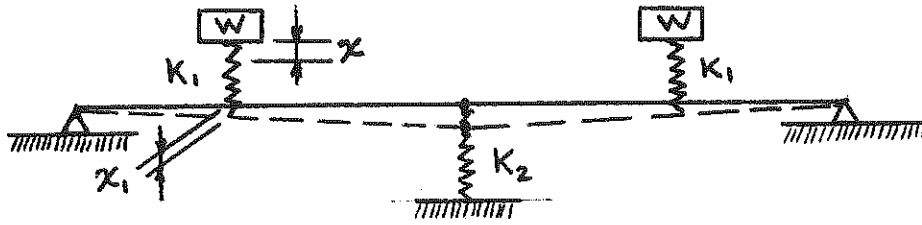
$$f_n = 838 \text{ c.p.s.}$$



Equivalent Vibration System No. 2

Figure 3-4

The system described above can be combined to form a third system as shown in Figure 3-5.



Combined System

Figure 3 - 5

$$-\frac{W}{g} \frac{d^2 x}{dt^2} = K_1 (x - x_1) \quad (3-14)$$

$$\frac{2K_1 (x - x_1)}{2K_2} (1/2) = x_1 \quad (3-15)$$

$$2K_2 x_1 = K_1 x - K_1 x_1$$

$$x_1 = \frac{K_1 x}{K_1 + 2K_2}$$

$$\frac{W}{g} \frac{d^2 x}{dt^2} + \left(K_1 - \frac{K_1^2}{K_1 + 2K_2} \right) x = 0 \quad (3-16)$$

$$\frac{d^2 x}{dt^2} + \left(\frac{K_1^2 + 2K_2 K_1 - K_1^2}{K_1 + 2K_2} \right) \frac{g}{W} x = 0 \quad (3-17)$$

Solution for frequency gives:

$$f_n = \frac{1}{2\pi} \left(\frac{2K_2 K_1 g}{(K_1 + 2K_2) W} \right)^{1/2} \quad (3-18)$$

$$K_2 = 5 \times 10^6 \text{ lb./in. as before}$$

$$K_1 = \text{Spring constant of beam}$$

$$= 384EI / l^3 = 5.22 \times 10^7 = 52.2 \times 10^6$$

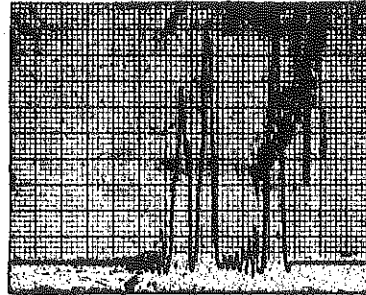
$$g = 32.2 \text{ ft./sec}^2$$

$$W = 920 \text{ lb.}$$

$$K_1 = \frac{384}{5} \left(\frac{EI}{l^3} \right) = \frac{384}{5} \left(\frac{(30 \times 10^6)(312.6)}{24^3} \right) \quad (3-19)$$

$$K_1 = 5.21 \times 10^7 \text{ lb/in}$$

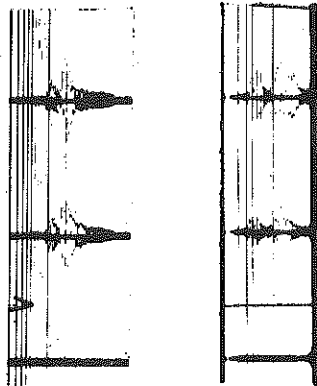
$$f_n = \frac{1}{2\pi} \left(\frac{2K_2 K_1 g}{(K_1 + 2K_2) W} \right)^{1/2} \quad (3-20)$$



Frequency = 100 cps

Typical Sanborne Trace Showing Vibrating Frequency of Weighing System (Lead Cell Output)

Figure 3-6



heavy lines are
1/10 second lines

Typical Traces from Accelerometers mounted on scale platform

Figure 3-7

$$= \frac{1}{2 (3.14)} \left(\frac{2 (5 \times 10^6) (52.2 \times 10^6) (32.2) (12)}{62.2 (920)} \right)^{1/2}$$

$$f_n = 300 \text{ cps}$$

The frequency of 175 cps obtained for System No. 1 approached the value of 100 cps determined in the field tests. (Figures 3-6 and 3-7).

In subsequent calculations the experimental value of 100 cps will be used. The difference in the theoretical and experimental values of the frequency could be caused by either damping at the hinges or by the inability of the recorder to detect vibrations of high frequency.

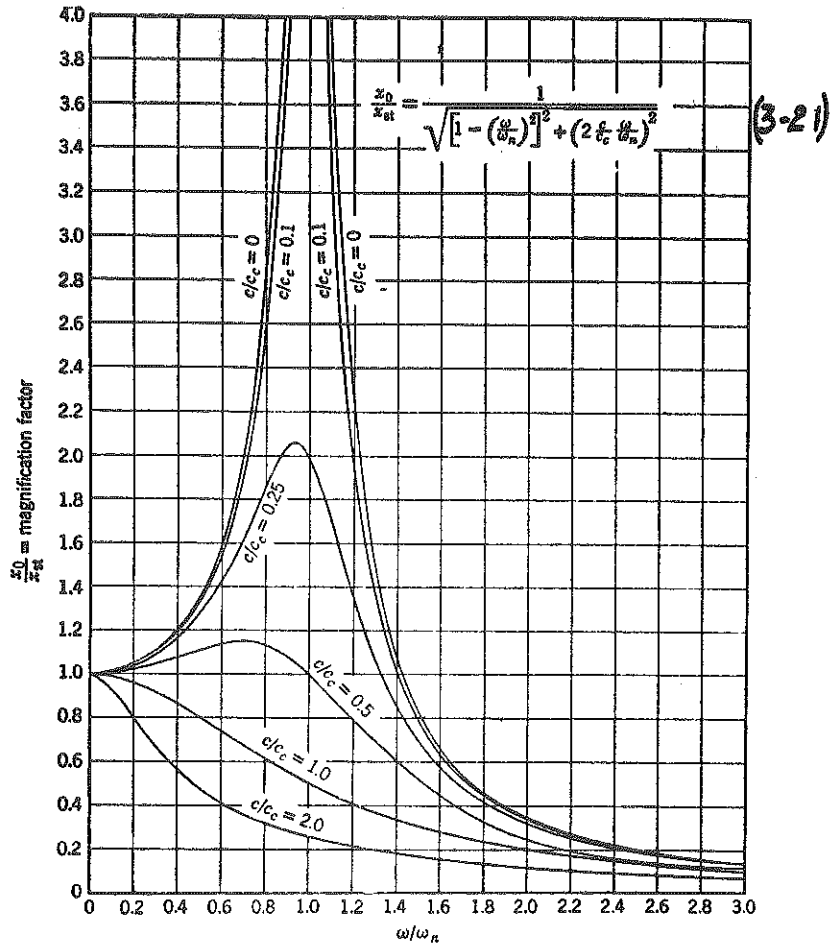
3. Comparison of Theoretically Calculated Frequencies to Experimental Values and to Applied Frequencies

Analysis of the assumed systems shown on the last several pages give natural frequencies in the range of 175 cps to 838 cps. In this investigation the frequencies applied to the scale were the cargo frequency of approximately three cycles per second and the undercarriage frequency of approximately 25 cycles per second. These values were obtained as the result of research done at the Kentucky Highway Materials Research Laboratory. Another frequency which might be applied to the system would be that resulting from wheel unbalance. For example, for a truck, with average size wheels, moving at 60 MPH a frequency of approximately 9.4 cps would be induced. The frequency of this vibration is too low to be a significant factor in this study.

It can be seen from the foregoing analysis that the applied frequencies are 1/10 or less of the natural frequency of approximately 100 cps. It will now be shown that these applied frequencies are far out of the range of any frequency that could cause a resonant or near resonant condition. Equation 3-21 (Figure 3-8) was developed to determine the dynamic magnification under various combinations of damping factors and ratios of applied and natural frequencies (2). The equation is solved using the two frequencies that occur with a truck (cargo and undercarriage), and assuming various damping factors for the scale platform. The results of the calculations appear in Table 3-2. The formula and terms used to make the above calculations appear in Figure 3-8 along with a number of graphical solutions for Equation 3-21.

4. Instrument Resonance

One further factor which should be considered is that of resonance of the recording instrument itself. The instrument used had a flat frequency response of 0 to 100 cps, that is the instrument would respond accurately to a signal having a frequency in this range. Since the upper frequency represents the highest which was encountered and this frequency is in the working range of the recording instrument used there will be no difficulty arising from instrument resonance. A recorder with a flat frequency response extending above the value of anticipated applied frequency should be used.



$$\omega = 2\pi f$$

$$\omega_n = 2\pi f_n$$

c/c_c = damping factor

Effects of damping and ratio of applied frequency to natural frequency on dynamic magnification

Figure 3-8

TABLE 3-2
DYNAMIC MAGNIFICATIONS

Valves of Percentage Critical Damping c/C_c	$F/f_n = 0.25$ Undercarriage Vibration	$F/f_n = 0.05$ Cargo Vibration
0	1.070	1.003
0.25	1.033	1.003
0.50	1.010	1.002

Dynamic Weight Measurements by Axle Housing Strain
and Tire Pressure Variations

The following is excerpted from a report of the testing program conducted during the summer of 1963 and a memorandum from R. E. Puckett to J. A. Dearing dated April 7, 1964.

It became necessary in our testing program to determine that the two platforms were measuring the weights applied to them. Axle-strain measurement was chosen to determine the action of a vehicle while it was on each of the platforms. Prior to this, we had no idea of the oscillation pattern of the weight of a vehicle while it was in the vicinity of our test site. We needed to determine the motion of a vehicle and its application of weight to the platforms.

Strain gages were mounted on the top and bottom of the rear axle housing of the test truck, and connected in a bridge network. (See Figure 1.) The truck was loaded with concrete beams. During the loading process, the strain-gage bridge was calibrated in weight units, using the recorder on loan from the Highway Dept. The complete instrumentation for the tests included an accelerometer mounted on the load, (Figure 2) the strain-gage bridge on the axle housing, and a light detector to locate the positions of the platforms along the pavement surface. The light detector was mounted in the end of a long pipe and attached to the side of the truck bed, close to the pavement surface.

Outputs from the three devices were recorded during speed runs across the platforms. Typical recorded traces are shown in Figure 3. Each is identified on the chart. The light detector trace shows distinct **chang** changes in light intensity in the vicinity of the platforms. These five distinct changes represent the white paint stripes on the pavement at the site, which were placed there earlier to camouflage the site. From the approach end of the site, the two platform locations coincide with the second and fourth paint stripes.

During the time these recordings were being made, the Sanborn equipment in the scale house recorded outputs of the two platforms. In this way, a correlation of the measurements from the two instrumentation systems could be made. Analysis of the recordings shows the variations of weight of a vehicle while it is on the platforms. The curves also show that the platforms are actually measuring the weight applied to them, but not necessarily the static weight. Only in isolated and unpredictable instances would the weight of a moving vehicle be its static weight while on the platforms. However, these tests showed that each of the two platforms (Taller-Cooper and Broken-Bridge) measures the load applied to it.

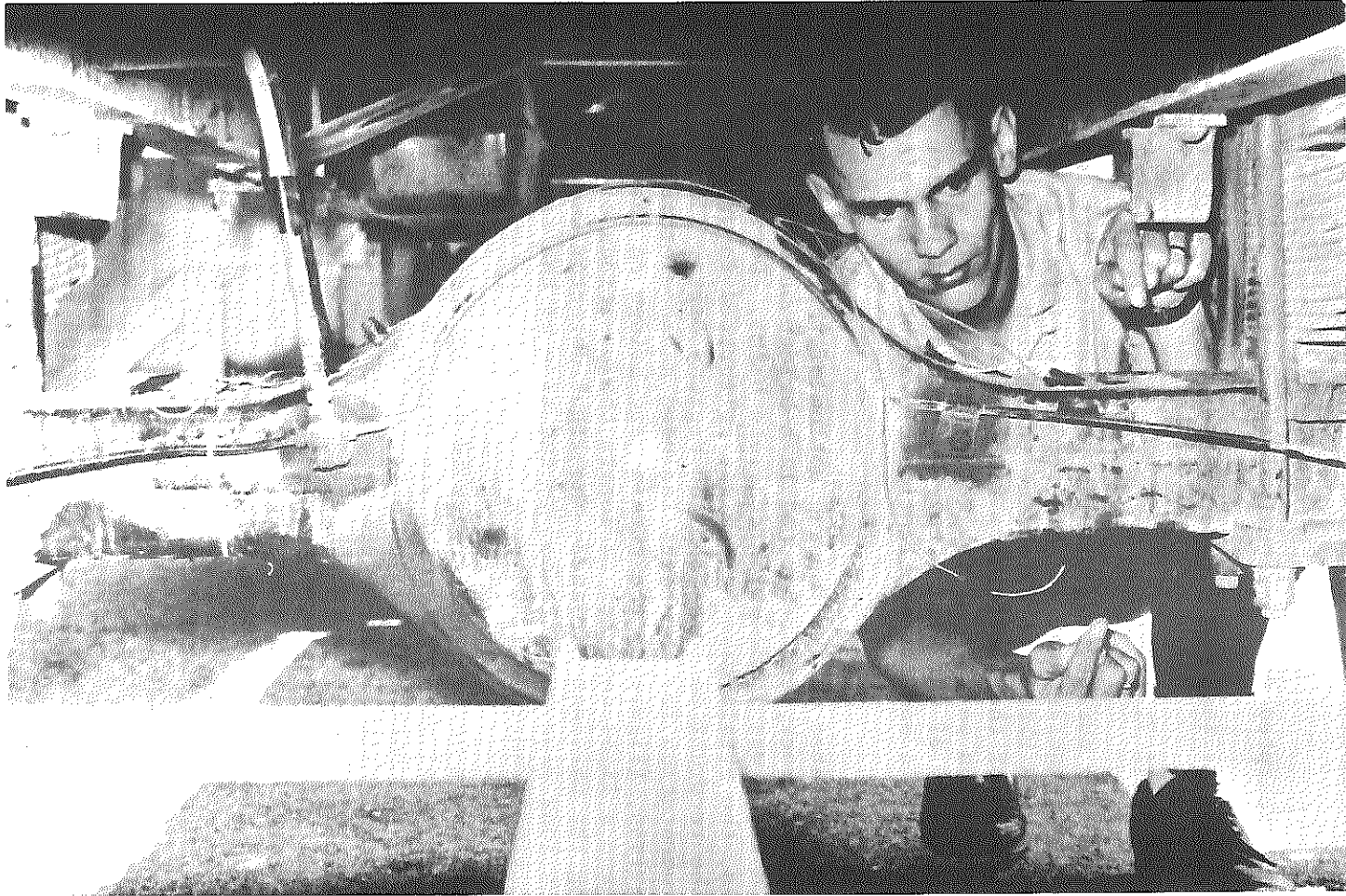


Figure 1.- Application of Strain Gages to Rear Axle Housing of Test Vehicle.

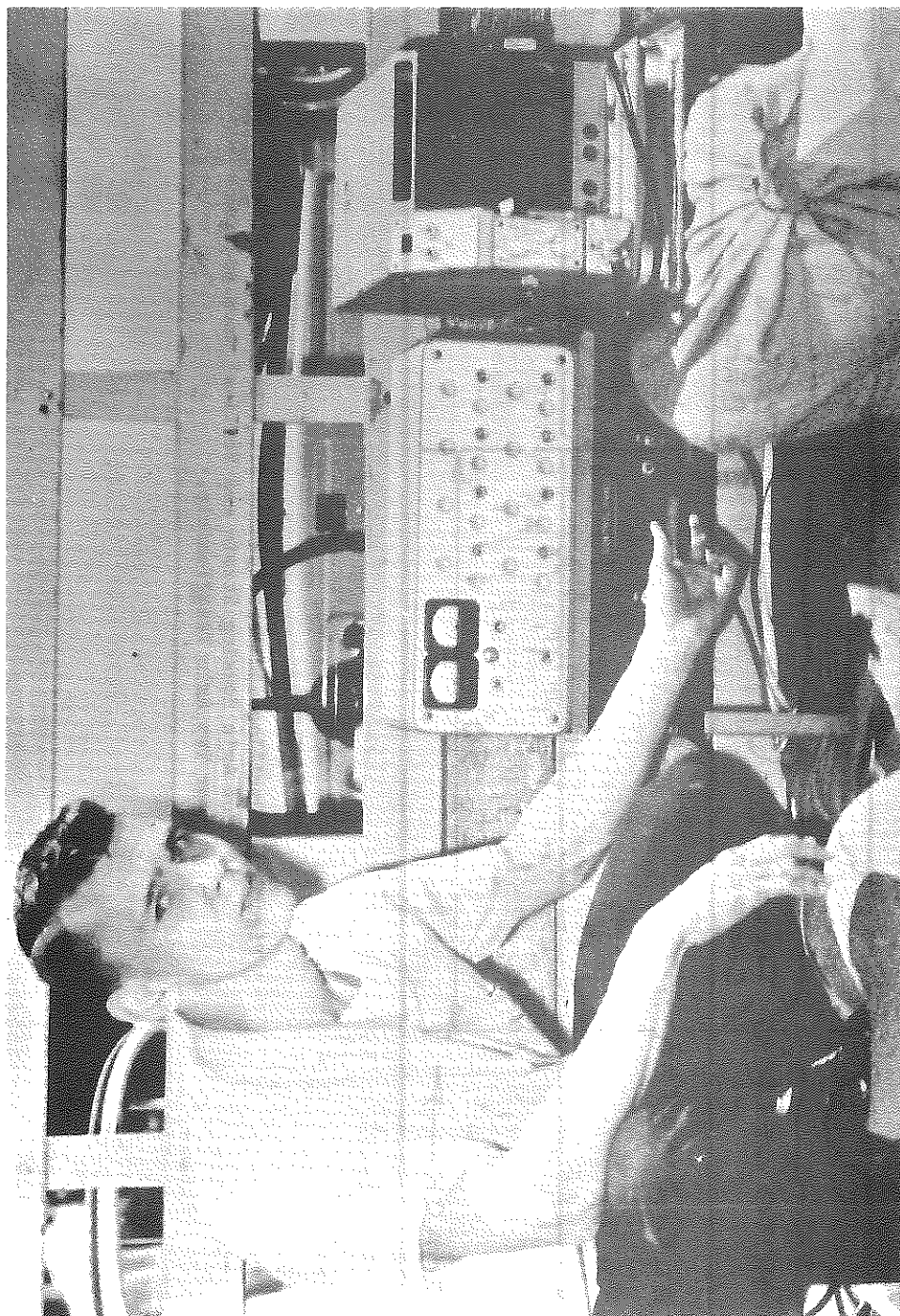


Figure 2.- Instrumentation in Rear of Test Vehicle.

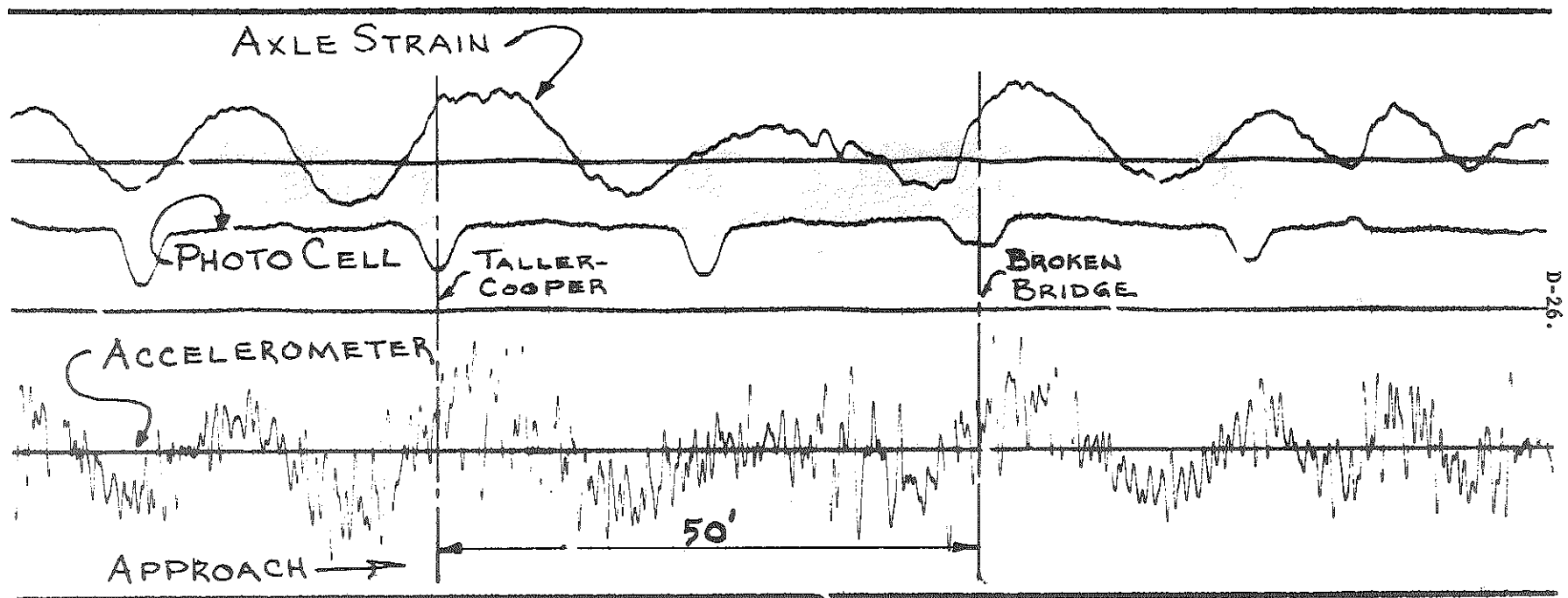


Figure 3. Oscillograph Tape Showing Simultaneous Recording of Axle Housing Strain and Vertical Acceleration for Two Axle Test Vehicle.

Taking into account experimental tolerances on errors, data reduction showed that for speeds up to 30 mph, and each platform preloaded at 100%, axle strain and acceleration measurements agree closely with weight measurements made by the platforms and Sanborn recorder system. Above 30 mph, their agreement is within 10%. The larger values of preload yielded best results over a range of speeds. (See Table 1).

Measurements showed that the test truck had a natural oscillation frequency in the vertical direction of about 2.4 cps. In addition, the maximum excursions of its dynamic weight from its static weight, in the vicinity of the test site, varied from 48% heavy to 39% less than its static weight. However, because of the physical construction of the site, the average deviation tended toward heavier than static.

This series of tests showed that the dynamic weight of a moving vehicle may be measured by either axle strain, acceleration of the load, or either of the two types of platforms used. The only basic requirement on all methods is that the instrumentation system be calibrated, in order to interpret the measurements in terms of weight.

TABLE 1

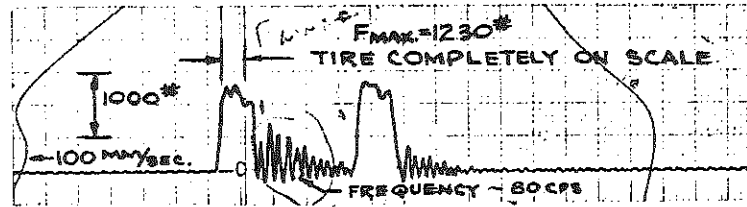
SUMMARY OF DEVIATIONS OF DYNAMIC WEIGHT FROM
STATIC AXLE HOUSING STRAIN MEASUREMENTS

	TALLER-COOPER			BROKEN BRIDGE		
	Preload (Steel Rods with Turnbuckles)			Preload (Coil Springs)		
	0%	50%	100%	0%	50%	100%
Percent deviation of weight, from axle strain mea- surements	-2 to 10	3 to 5	2 to 4	0.5 to 5.5	6 to 8	2 to 12.5
Percent deviation of weight, from Sanborn charts, correlated with axle strain	1	1.5 to 4	0 to 6	0.5 to 3	20 to 22	10 to 17

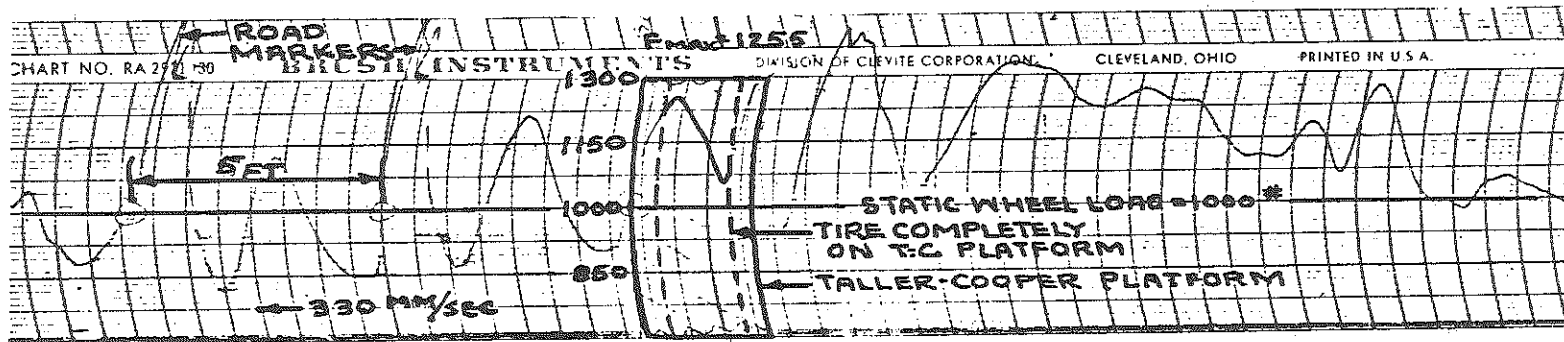
Research engineers from Purdue University visited the I-64 Test Site during August, 1963. They made a few test runs over the Taller-Cooper scale with a test vehicle which was instrumented to record the variations in tire pressure induced by the movement of the vehicle along the highway.

The following is part of a letter report on the outcome of the tests submitted by Mr. C. C. Wilson of Purdue. The pressure variation and dynamic scale recordings follow the text in Figures 4 & 5.

Two of the records which were made on August 7 at the Shelbyville weighing station are enclosed. Both tests were conducted at the same speed of 30 mph and were made using the Taller-Cooper platform only. The first test was made with no preload and the second with a 2000 lb. preload. A comparison of the dynamic force measurement with the Taller-Cooper platform measurement shows that the wave shapes are similar while the tire is completely on the platform. The maximum recorded forces compared well for the no preload condition but not so well for the preloaded condition.



TALLER-COOPER LOAD PLATFORM
NO PRELOAD



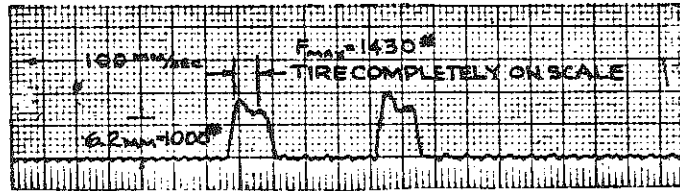
DYNAMIC TIRE FORCE MEASUREMENT

COMPARISON OF TALLER-COOPER LOAD PLATFORM
MEASUREMENT WITH THE PURDUE UNIVERSITY
DYNAMIC TIRE FORCE MEASURING INSTRUMENT.

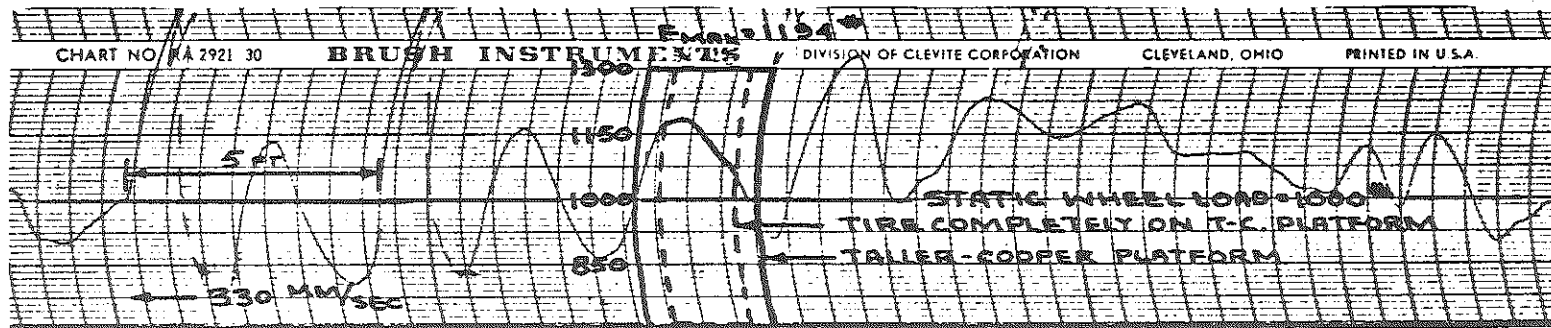
Vehicle #210

traveling at 30 mph. I-64, Shelbyville,
Kentucky, 8-7-63 C. Wilson, G. Kibbee.

Figure 4



TALLER-COOPER LOAD PLATFORM
2000 LB PRELOAD



DYNAMIC TIRE FORCE MEASUREMENT

COMPARISON OF TALLER-COOPER LOAD PLATFORM
MEASUREMENT WITH THE PURDUE UNIVERSITY
DYNAMIC TIRE FORCE MEASURING INSTRUMENT.
Vehicle #210
traveling at 30 mph. I-64, Shelbyville,
Kentucky, 8-7-63 C. Wilson, G. Kibbee.

Figure 5

APPENDIX E

THE EPOXY RESIN MORTAR LEVELING COURSE



METHOD OF PLACEMENT OF EPOXY RESIN LEVELING COURSE

PREPARED BY KENTUCKY DEPARTMENT OF HIGHWAYS, DIVISION OF RESEARCH

Work for the Placement of an Epoxy Resin mortar leveling course can be broken down into two basic parts - that of surface preparations and that of coating. Each of these parts of the total process will be discussed in detail, giving approximate quantities and a recommended time schedule. Also, at the end of this discussion is a list of required materials, the use that will be made of them, and a possible vendor in the Lexington area.

Surface PreparationBroom Sweeping

The area to be coated shall be thoroughly swept and thereby ridded of all loose dirt and debris.

Materials Stuck to the Surface

If tars or other materials are present they should be removed with the proper solvent.

Hose Cleaning

Water washing with a fine stream under pressure should then follow to remove all remaining mud and any other loose material.

Acid Etching

While the surface is still damp it shall be acid etched with Muriatic acid. The concentrate of the acid solution shall be 10% and the application rate shall be 3 pints of solution per square yard. The acid etching should be carried out beyond the point that any visible reaction is still going on. Fifteen minutes is a guess at required time. It is recommended that areas the width of the road and several yards long be etched in one continuous application.

Second Water Wash

Acid Etching should be followed by a water wash.

Neutralization

A 1% solution shall be made from commercially available ammonia to neutralize the etched surface. An application rate of 3 pints of solution per ~~year~~^{sq} shall be used. Blue litmus test will tell when neutralization has been achieved.

Final Water Wash

Through final washing shall follow ammonia application.

Thorough Drying

A drying period sufficient to allow complete drying shall follow the cleaning process.

COATING

Priming

Surface shall be primed with a thin coating of the resin. The thickness will be just sufficient to give full coverage.

Mixing

The A and B components of the resins are mixed in equal amounts. The measurement of these quantities should be accurately done. Sand shall be stirred into this epoxy as rapidly as possible since over mixing hastens the setting reaction. The ratio of sand to resin shall be 2.75 to 1 by volume. Sand shall be clean dry silica of approximately the following gradation: 100% passing # 16, 99% passing # 30, 57.4% passing # 50, 21.9% passing # 100, 2.0% passing # 200;

Placing

The sand resin mixture shall be placed approximately 1/8" thick with trowels like cement. The trowel finish shall be as good as possible

to fill low places and obtain a smooth surface. The self leveling property of the resin should insure a level finish.

Sanding

In order to obtain a durable, non-skid surface, the area is sprinkled with crystal silica (coarse) sand just before it hardens. This usually will be twenty to thirty minutes after placement.

Working Temperature

Temperatures in excess of 60°F are necessary for epoxy placement.

Setting Period

A twenty-four hour period will usually furnish sufficient setting time.

MATERIALS (for 100' job)

ITEM	USE
1. Xylene or Xylol (5 gals)	Epoxy Solvent (cleaning)
2. Hand cleaner	--
3. Rags	General cleaning
4. Muriatic Acid one carboy	Etching
5. 2 gals Ammonia	Neutralization
6. Hose & Nozzle	Washing of surface
7. Stiff bristled scrub brushes with long handles - 6	Apply acid while scrubbing
8. Plastic Coated gloves (4 pr.)	Hand protection
9. 6 cylinder mold cans	Measurement
10. 2 18" squeegee long handles	Priming
11. 4 pair goggles	Eye protection (preparation & coating)
12. 2 buckets (2 gals)	Cleaning materials
13. Stiff bristled brooms (2)	Sweep surface
14. 2 steel trowel (rectangular)	Work Resin Mortar
15. 2 24 inch squeegee long handles	Work mortar
16. 1 doz. wooden stirring sticks	Mixing
17. Portable drill with mixer blade	Mix Epoxy Mortar
18. Chipping hammer	Remove hardened misplaced spots
19. 2 molasses gate valve	Enable purging from drum

APPENDIX F

TABULAR SUMMARIES

OUTPUT OF DATA ANALYSIS PROGRAM



Table 1.

Taller - Cooper Scale
All Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	271	119	152
<u>Static Wt. (X)</u>			
Max. Value	20000 *	20000	17980
Min. Value	1100	1100	1680
Avg. Value	6558	6587	6516
Std. Dev.	\pm 3087 *	\pm 3296	\pm 2914
<u>Dynamic Wt. (Y)</u>			
Max. Value	20000	20100	19500
Min. Value	1200	1200	2400
Avg. Value	7341	7144	7470
Std. Dev.	\pm 3269	\pm 3460	\pm 3108
Correlation Coefficient	0.97342	0.97296	0.97768
Regression Line Equation	$Y=581+1.031X$	$Y=416+1.021X$	$Y=676+1.043X$
Std. Error of Estimate	\pm 749 *	\pm 799	\pm 653

* All Weights, Standard Deviations and Standard Errors
are given in pound units.

Table 2.

Taller - Cooper Scale

All Axles - 12 Kip Preload - Rod & Turnbuckle

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	961	512	449
<u>Static Wt. (X)</u>			
Max. Value	22120	22120	19120
Min. Value	1060	1060	2240
Avg. Value	7049	7222	6851
Std. Dev.	\pm 3571	\pm 3704	\pm 3403
<u>Dynamic Wt. (Y)</u>			
Max. Value	23600 25020	25020	23352
Min. Value	1251	1251	11668
Avg. Value	8091	8203	7964
Std. Dev.	\pm 3994	\pm 4114	\pm 3847
Correlation Coefficient	0.97926	0.98081	0.97777
Regression Line Equation	$Y=372+1.095X$	$Y=333+1.090X$	$Y=391+1.105X$
Std. Error of Estimate	\pm 809	\pm 802	\pm 808

Table 3.
Broken Bridge Scale
All Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	272	119	153
<u>Static Wt.</u> (X)			
Max. Value	20000	20000	17980
Min. Value	1100	1100	1680
Avg. Value	6547	18900 6	6516
Std. Dev.	\pm 3087	\pm 3296	\pm 2914
<u>Dynamic Wt.</u> (Y)			
Max. Value	21683	18026	21683
Min. Value	1045	1045	2612
Avg. Value	6738	6320	7063
Std. Dev.	\pm 3435	\pm 3472	\pm 3370
Correlation Coefficient	0.96359	0.96787	0.97484
Regression Line Equation	$Y = -281 + 1.07X$	$Y = -396 + 1.020X$	$Y = -282 + 1.127X$
Std. Error of Estimate	\pm 918	\pm 873	\pm 752

Table 4.
Broken Bridge Scale
All Axles - 12 Kip Preload - Coil Spring

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	961	519	442
<u>Static Wt. (X)</u>			
Max. Value	22120	22120	19120
Min. Value	1060	1060	2240
Avg. Value	7049	7252	16880
Std. Dev.	± 3571	± 3722	± 3370
<u>Dynamic Wt. (Y)</u>			
Max. Value	25559	25559	21607
Min. Value	527	527	2108
Avg. Value	7528	23028	7646
Std. Dev.	± 4072	± 4155	± 3969
Correlation Coefficient	0.96848	0.96969	0.97666
Regression Line Equation	Y= -257+1.104X	Y= -423+1.083X	Y= -189+1.150X
Std. Error of Estimate	± 1014	± 1015	± 852

Table 6
 Taller - Cooper Scale
 Front Axles - Zero Preload

Item	All Speeds	Speed 20 20 MPH	Speed > 20 MPH
No of Axles in Sample	85	38	47
<u>Static Wt. (X)</u>			
Max. Value	9560	9560	9460
Min. Value	2940	3260	2940
Avg. Value	5968	6145	5824
Std. Dev.	\pm 1731	\pm 1915	\pm 1552
<u>Dynamic Wt. (Y)</u>			
Max. Value	10200	10200	9900
Min. Value	3600	3600	3600
Avg. Value	6730	6663	6300
Std. Dev.	1862	2047	1695
Correlation Coefficient	0.95168	0.97934	0.93525
Regression Line Equation	$Y=623+1.023X$	$Y=230+1.047X$	$Y=836+1.021X$
Std. Error of Estimate	\pm 585	\pm 410	\pm 600

Table 6.

Taller - Cooper Scale

Front Axles - 12 Kip Preload - Rod & Turnbuckle

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	272	139	133
<u>Static Wt. (X)</u>			
Max. Value	10200	10100	10200
Min. Value	2140	2140	2500
Avg. Value	6282	6475	6080
Std. Dev.	\pm 1894	\pm 1739	\pm 2025
<u>Dynamic Wt. (Y)</u>			
Max. Value	12510	11676	12510
Min. Value	2085	2085	2502
Avg. Value	7122	7206	7035
Std. Dev.	\pm 2304	\pm 2084	\pm 2511
Correlation Coefficient	0.97685	0.97181	0.98458
Regression Line Equation	$Y = -343 + 1.188X$	$Y = -338 + 1.165X$	$Y = -389 + 1.221X$
Std. Error of Estimate	\pm 493	\pm 492	\pm 440

Table 7.
 Broken Bridge Scale
 Front Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	271	38	47
<u>Static Wt. (X)</u>			
Max. Value	9560	9560	9460
Min. Value	2940	3260	2940
Avg. Value	5968	6145	5824
Std. Dev.	\pm 1731	\pm 1915	\pm 1552
<u>Dynamic Wt. (Y)</u>			
Max. Value	10450	9666	10450
Min. Value	2873	3135	2873
Avg. Value	6072	5987	6141
Std. Dev.	\pm 1875	\pm 1909	\pm 1844
Correlation Coefficient	0.95760	0.96570	0.97445
Regression Line Equation	$Y = -116 + 1.037X$	$Y = 71 + 0.963X$	$Y = -600 + 1.158X$
Std. Error of Estimate	\pm 540	\pm 496	\pm 413

Table 8.
Broken Bridge Scale
Front Axles - 12 Kip Preload - Coil Spring

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	272	140	132
<u>Static Wt. (X)</u>			
Max. Value	10200	10100	10200
Min. Value	2140	2140	2500
Avg. Value	6282	6445	6110
Std. Dev.	\pm 1894	\pm 1739	\pm 2032
<u>Dynamic Wt. (Y)</u>			
Max. Value	12648	10803	12648
Min. Value	2108	2108	2108
Avg. Value	6680	6641	6721
Std. Dev.	\pm 2222	\pm 1962	\pm 2466
Correlation Coefficient	0.96743	0.96954	0.97652
Regression Line Equation	$Y = -448 + 1.135X$	$Y = -410 + 1.094X$	$Y = -520 + 1.185X$
Std. Error of Estimate	\pm 562	\pm 481	\pm 531

Table 9.
 Taller - Cooper Scale
 Second Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	271	47	38
<u>Static Wt. (X)</u>			
Max. Value	20000	17980	20000
Min. Value	3640	4700	3640
Avg. Value	8518	8622	8388
Std. Dev.	\pm 3550	\pm 3251	\pm 3884
<u>Dynamic Wt. (Y)</u>			
Max. Value	20100	19500	20100
Min. Value	4200	5700	4200
Avg. Value	9285	9568	8936
Std. Dev.	\pm 3753	\pm 3380	\pm 4143
Correlation Coefficient	0.96935	0.98301	0.96013
Regression Line Equation	$Y=556+1.025X$	$Y =756+1.022X$	$Y=347+1.024X$
Std. Error of Estimate	\pm 920	\pm 620	\pm 1159

Table 10.
 Taller - Cooper Scale
 Second Axles - 12 Kip Preload - Rod & Turnbuckle

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	272	140	132
<u>Static Wt. (X)</u>			
Max. Value	22120	22120	19120
Min. Value	1060	1060	2240
Avg. Value	8881	8908	8852
Std. Dev.	\pm 3968	\pm 4164	\pm 3749
<u>Dynamic Wt. (Y)</u>			
Max. Value	25000 25020	25020	23352
Min. Value	1251	1251	2085
Avg. Value	23869 23869	9767	9976
Std. Dev.	\pm 4502	\pm 4731	\pm 4243
Correlation Coefficient	0.98233	0.98832	0.97549
Regression Line Equation	$Y = -29 + 1.114X$	$Y = -235 + 1.123X$	$Y = 203 + 1.104X$
Std. Error of Estimate	\pm 842	\pm 721	\pm 933

Table 11.
 Broken Bridge Scale
 Second Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	85	38	47
<u>Static Wt. (X)</u>			
Max. Value	20000	20000	17980
Min. Value	3640	3640	4700
Avg. Value	8518	8388	8622
Std. Dev.	\pm 3550	\pm 3884	\pm 3251
<u>Dynamic Wt. (Y)</u>			
Max. Value	21683	18026	21683
Min. Value	3135	3135	4180
Avg. Value	8688	7988	9254
Std. Dev.	\pm 4127	\pm 4106	\pm 4057
Correlation Coefficient	0.95907	0.96137	0.97691
Regression Line Equation	$Y = -809 + 1.115X$	$Y = -536 + 1.016X$	$Y = -1257 + 1.219X$
Std. Error of Estimate	\pm 1168	\pm 1129	\pm 867

Table 12.
Broken Bridge Scale
Second Axles - 12 Kip Preload - Coil Spring

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	272	141	131
<u>Static Wt. (X)</u>			
Max. Value	22120	22120	19120
Min. Value	1060	1060	2240
Avg. Value	8881	8911	8848
Std. Dev.	\pm 3968	\pm 4150	\pm 3763
<u>Dynamic Wt. (Y)</u>			
Max. Value	25559	25559	21607
Min. Value	527	527	2371
Avg. Value	9418	8935	9938
Std. Dev.	\pm 4700	4789	4546
Correlation Coefficient	0.96447	0.96608	0.97741
Regression Line Equation	$Y = -727 + 1.142X$	$Y = -1001 + 1.115X$	$Y = -509 + 1.181X$
Std. Error of Estimate	\pm 1241	\pm 1237	\pm 960

Table 13.
 Taller - Cooper Scale
 Third Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	53	22	31
<u>Static Wt. (X)</u>			
Max. Value	15020	15020	13740
Min. Value	1100	1100	2800
Avg. Value	5544	5888	5300
Std. Dev.	\pm 2716	\pm 3281	\pm 2198
<u>Dynamic Wt. (Y)</u>			
Max. Value	18000	15600	18000
Min. Value	1200	1200	3000
Avg. Value	6379	6572	6241
Std. Dev.	\pm 3062	\pm 3415	\pm 2776
Correlation Coefficient	0.96133	0.97280	0.95925
Regression Line Equation	$Y=371+1.084X$	$Y=610+1.013X$	$Y= -179+1.211X$
Std. Error of Estimate	\pm 842	\pm 791	\pm 783

Table 14.
 Taller - Cooper Scale
 Third Axles - 12 Kip Preload - Rod & Turnbuckle

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	202	113	89
<u>Static Wt. (X)</u>			
Max. Value	19000	19000	18100
Min. Value	2100	2100	2240
Avg. Value	6252	6547	5877
Std. Dev.	\pm 3529	\pm 3662	\pm 3315
<u>Dynamic Wt. (Y)</u>			
Max. Value	22935	22935	19182
Min. Value	1668	2919	1668
Avg. Value	7578	7760	7346
Std. Dev.	\pm 4024	\pm 4059	\pm 3966
Correlation Coefficient	0.96944	0.96766	0.97552
Regression Line Equation	$Y=668+1.105X$	$Y=737+1.073X$	$Y=488+1.167X$
Std. Error of Estimate	\pm 986	\pm 1024	\pm 873

Table 15.
Broken Bridge Scale
Third Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	53	22	31
<u>Static Wt. (X)</u>			
Max. Value	15020	15020	13740
Min. Value	1100	1100	2800
Avg. Value	5544	5888	5300
Std. Dev.	\pm 2716	\pm 3281	\pm 2198
<u>Dynamic Wt. (Y)</u>			
Max. Value	159986	15936	15936
Min. Value	1045	1045	3135
Avg. Value	5949	5794	6058
Std. Dev.	\pm 3138	\pm 3687	\pm 2676
Correlation Coefficient	0.95680	0.96885	0.96757
Regression Line Equation	$Y = -179 + 1.105X$	$Y = -617 + 1.089X$	$Y = -184 + 1.178X$
Std. Error of Estimate	\pm 913	\pm 914	\pm 676

Table 16.
Broken Bridge Scale
Third Axles - 12 Kip Preload - Coil Spring

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	202	112	90
<u>Static Wt. (X)</u>			
Max. Value	19000	19000	18100
Min. Value	2100	2100	2240
Avg. Value	6252	6555	5875
Std. Dev.	\pm 3529	\pm 3677	\pm 3297
<u>Dynamic Wt. (Y)</u>			
Max. Value	20026	20026	19762
Min. Value	2108	2108	2635
Avg. Value	6928	7006	6830
Std. Dev.	\pm 4056	\pm 4128	\pm 3964
Correlation Coefficient	0.96416	0.96684	0.96800
Regression Line Equation	$Y = -1 + 1.108X$	$Y = -108 + 1.085X$	$Y = -6.7 + 1.164X$
Std. Error of Estimate	\pm 1074	\pm 1053	\pm 995

Table 17.
 Taller - Cooper Scale
 Fourth & Fifth Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	49	21	28
<u>Static Wt. (X)</u>			
Max. Value	16080	14860	16080
Min. Value	1680	2920	1680
Avg. Value	5217	4855	5489
Std. Dev.	\pm 2772	\pm 2568	\pm 2887
<u>Dynamic Wt. (Y)</u>			
Max. Value	17400	15900	17400
Min. Value	2400	3300	2400
Avg. Value	5993	5371	6460
Std. Dev.	\pm 2962	\pm 2695	\pm 3065
Correlation Coefficient	0.98575	0.98662	0.98866
Regression Line Equation	$Y=499+1.053X$	$Y=343+1.036X$	$Y=699+1.050X$
Std. Error of Estimate	\pm 498	\pm 439	\pm 463

Table 18.

Taller - Cooper Scale

Fourth & Fifth Axles - 12 Kip Preload - Rod & Turnbuckle

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	215	120	95
<u>Static Wt. (X)</u>			
Max. Value	18140	18140	16220
Min. Value	1900	1900	2320
Avg. Value	6450	6757	6062
Std. Dev.	\pm 3859	\pm 4191	\pm 3355
<u>Dynamic Wt. (Y)</u>			
Max. Value	19182	19182	18765
Min. Value	2502	2502	3336
Avg. Value	7552	7950	7049
Std. Dev.	\pm 4242	\pm 4616	\pm 3653
Correlation Coefficient	0.98512	0.98691	0.98156
Regression Line Equation	$Y=568+1.083X$	$Y=604+1.087X$	$Y=569+1.069X$
Std. Error of Estimate	\pm 729	\pm 745	\pm 698

Table 19.
 Broken Bridge Scale
 Fourth & Fifth Axles - Zero Preload

Item	All Speeds	Speed \leq 20 MPH	Speed $>$ 20 MPH
No. of Axles in Sample	49	21	28
<u>Static Wt. (X)</u>			
Max. Value	16080	14860	16080
Min. Value	1680	2920	1680
Avg. Value	5217	4855	5489
Std. Dev.	\pm 2772	\pm 2568	\pm 2887
<u>Dynamic Wt. (Y)</u>			
Max. Value	16197	15675	16197
Min. Value	2351	2351	2612
Avg. Value	5363	4453	6045
Std. Dev.	\pm 3044	\pm 2821	\pm 3027
Correlation Coefficient	0.96104	0.96963	0.97203
Regression Line Equation	$Y = -142 + 1.055X$	$Y = -719 + 1.065X$	$Y = 451 + 1.019X$
Std. Error of Estimate	\pm 841	\pm 691	\pm 711

Table 20.
Broken Bridge Scale
Fourth & Fifth Axles - 12 Kip Preload - Coil Spring

Item	All Speeds	Speed \leq 23 MPH	Speed $>$ 23 MPH
No. of Axles in Sample	215	126	89
<u>Static Wt. (X)</u>			
Max. Value	18140	18140	16220
Min. Value	1900	1900	2320
Avg. Value	6450	6911	5797
Std. Dev.	\pm 3859	\pm 4249	\pm 3113
<u>Dynamic Wt. (Y)</u>			
Max. Value	23451	23451	17918
Min. Value	1844	1844	2898
Avg. Value	6774	6990	6468
Std. Dev.	\pm 4258	\pm 4737	\pm 3445
Correlation Coefficient	0.97183	0.97604	0.97193
Regression Line Equation	$Y = -142 + 1.072X$	$Y = -530 + 1.088X$	$Y = 232 + 1.076X$
Std. Error of Estimate	\pm 1004	\pm 1030	\pm 810

Table 21.
 Taller - Cooper Scale
 All Speeds - 12 Kip Preload - Coil Spring

Item	All Axles	Front Axles	Second Axles
No. of Axles in Sample	309	88	88
<u>Static Wt. (X)</u>			
Max. Value	24100	11740	19440
Min. Value	1120	2500	1120
Avg. Value	7946	6670	10162
Std. Dev.	± 4018	± 1870	± 4268
<u>Dynamic Wt. (Y)</u>			
Max. Value	21385	12189	20743
Min. Value	1710	2993	1710
Avg. Value	9115	7570	11357
Std. Dev.	± 4067	± 2146	± 4424
Correlation Coefficient	0.97517	0.95174	0.98407
Regression Line Equation	$Y=1272+0.987X$	$Y=286+1.092X$	$Y=992+1.020X$
Std. Error of Estimate	± 900	± 659	± 787

Table 22.

Taller - Cooper Scale

All Speeds - 12 Kip Preload - Coil Spring

Item	Third Axles	Fourth & Fifth Axles
No. of Axles in Sample	73	60
<u>Static Wt. (X)</u>		
Max. Value	24100	15960
Min. Value	2080	2280
Avg. Value	7838	6700
Std. Dev.	± 4824	± 3437
<u>Dynamic Wt. (Y)</u>		
Max. Value	21385	18177
Min. Value	3207	4063
Avg. Value	9063	8157
Std. Dev.	± 4471	± 3689
Correlation Coefficient	0.96735	0.98139
Regression Line Equation	$Y=2035+0.897X$	$Y=1101+1.053X$
Std. Error of Estimate	± 1132	± 705

Table 23.

Beam Type Scale

All Speeds - Zero Preload

Item	All Axles	Front Axles	Second Axles
No. of Axles in Sample	141	43	43
<u>Static Wt. (X)</u>			
Max. Value	17560	12480	17560
Min. Value	1500	2320	3100
Avg. Value	7137	6064	8280
Std. Dev.	± 3604	± 2195	± 4065
<u>Dynamic Wt. (Y)</u>			
Max. Value	19250	12325	19250
Min. Value	2375	2375	3500
Avg. Value	7713	6454	8713
Std. Dev.	± 3659	± 2272	± 4095
Correlation Coefficient	0.96807	0.96977	0.97514
Regression Line Equation	$Y=699+0.983X$	$Y=367+1.004X$	$Y=580+0.982X$
Std. Error of Estimate	± 917	± 554	± 908

Table 24.

Beam Type Scale

All Speeds - Zero Preload

Item	Third Axles	Fourth & Fifth Axles
No. of Axles in Sample	28	27
<u>Static Wt. (X)</u>		
Max. Value	14920	16440
Min. Value	3120	1500
Avg. Value	7093	7071
Std. Dev.	± 3294	± 4319
<u>Dynamic Wt. (Y)</u>		
Max. Value	14500	17813
Min. Value	2943	3000
Avg. Value	7933	7898
Std. Dev.	± 3503	± 4249
Correlation Coefficient	0.94993	0.96913
Regression Line Equation	$Y=768+1.010X$	$Y=1156+0.953X$
Std. Error of Estimate	± 1095	± 1049