DYNAMIC ASPECTS OF VEHICLE SIZE AND WEIGHT

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Discussion of a Paper Entitled
"Variations in Axle Weights of Moving Trucks"
by Professors David K. Blythe, John A. Dearinger,
and Russell E. Puckett of the University of Kentucky
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In preparing this discussion the author has used data associated with three Highway Planning and Research projects being conducted by the Michigan State Highway Department in cooperation with the U. S. Department of Commerce, Bureau of Public Roads: Research Projects 55 F-42 ("A Study of Dynamic Load Aspects of Truck Size and Weight"), 52 F-26 ("Automatic Weighing of Vehicles in Motion and Collection of Traffic Data by Electronic Methods"), and 62 F-73 ("Evaluation and Application Study of General Motors Corporation Rapid Travel Profilometer").

This research work is being conducted under general supervision of W. W. McLaughlin, Testing and Research Engineer, and under the immediate supervision of E. A. Finney, Director, Research Laboratory Division, Michigan State Highway Department.

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SYNOPSIS

This discussion gives dynamic axle load data in support of Professor Blythe's general statements that such data should be collected, evaluated, and used in formulating future pavement design critera, and that further research should be conducted in vehicle dynamics, considering variations in axle loads due to vehicular, driver, and environmental characteristics.

Factors related to weighing vehicles in motion to determine static weight are covered, as well as those associated with the dynamic aspects of vehicle size and weight. The magnitude and frequency of impact loads determined from current Michigan studies are included for further illustration of the problems related to dynamic load determinations.

Introduction

This presentation is a resume of the dynamic load-highway problem, as part of a discussion of a paper entitled "Variations in Axle Weights of Moving Trucks" presented by Professor David K. Blythe at this meeting. The authors, in addition to describing their method of determining dynamic axle loads, show how actual loads applied to highway surfaces vary considerably above or below static weights. They also recommend that dynamic axle load values be considered in future pavement design criteria, and that research be conducted in the field of vehicle dynamics to consider variations in axle loads due to vehicular, driver, and environmental characteristics.

The authors have touched upon three very important and timely subjects which I wish to cover briefly in this discussion under the following headings:

1. Weighing vehicles in motion by electronic scales.
2. Determining dynamic effects of vehicles.
3. Impact loads caused by moving vehicles.

These subjects are of concern not only to highway administrators and legislators, but also to vehicle manufacturers and to transport people.

WEIGHING VEHICLES IN MOTION

The history of research related to weighing vehicles in motion is well documented in Professor Blythe's paper, including projects both in Europe and America.

Professor Blythe has described the project on weighing vehicles in motion being conducted under his direction by the Civil Engineering Department of the University of Kentucky, sponsored jointly with the Kentucky Research Foundation, the Kentucky Department of Highways, and the Bureau of Public Roads. It is understood that the Kentucky project is concerned primarily with study and development of a suitable electronic scale weighing platform.

Concurrent with the Kentucky project, the Michigan State Highway Department, also in cooperation with the Bureau of Public Roads, is developing a complete automatic weighing and traffic data collection system composed of the following basic subsystems:

1. An automatic weighing system consisting of four bridge-type sensing devices or scales spaced at different intervals. This system determines vehicle speed, axle load, and axle spacing.

2. An infrared light sensing system which will determine vehicle length, width, and height.

3. A vehicle classification system which will determine number and speed of commercial vehicles by traffic lanes.

This project started officially in 1960, and is now entering its third and most advanced stage which is to be completed by the end of 1965. The completed system is intended to perform two major functions:

1. It may serve simply to monitor vehicles for violation of Michigan's size and weight regulations, and
2. It may serve as an automatic traffic data collection system when such information is desired.

However, in addition to these two functions, the system may become an invaluable research tool in connection with current studies concerning dynamic characteristics of vehicles in motion and related axle loads.

The transport industry will benefit from the Kentucky and Michigan studies by the reduction and possible elimination of delays at weighing stations. On the other hand, highway departments will be in a position to monitor commercial traffic more effectively to weed out illegal operators.

Professor Blythe has demonstrated in his paper how electronic scales may become a useful tool in detecting dynamic variations in axle weights, and, in addition, certain characteristics of vehicles under controlled circumstances.

DETERMINING DYNAMIC EFFECTS OF VEHICLES

Present highway design criteria for pavements and structures, regulatory legislation concerning weight enforcement, and taxes are based exclusively on static load conditions. The relationship between pavement design and performance in service is of great concern to highway administrators. While static and dynamic axle loads have been measured with reasonable acuuracy at selected points along pavements or on structures, engineering data remain to be determined by highway engineers pertaining to the magnitude and distribution of axle loads imposed by commercial vehicles in normal travel over all types of pavement and structures. Automotive engineers have determined such data to a certain degree for vehicle design purposes.

From the standpoint of the highway engineer, the overall problem involves four basic areas of study:

1. Determination of axle load fluctuations for single and tandem axle assemblies, under various load, speed, and pavement conditions.

2. Determination of weight distribution between the various axles of a vehicle in motion.

3. Determination of the factors in vehicle construction having significant bearing on pavement design criteria.

4. Determination of relative effects on pavement surfaces and structures caused by different types of commercial vehicles.

The dynamic response of vehicles to the road profile has received the attention of vehicle manufacturers for years, because of its relationship to vehicle performance and ride characteristics.

The transport industry is vitally interested in vehicle maintenance, performance reliability, cargo safety, and driver comfort, as these are affected by the dynamic characteristics of the road-vehicle system.

Highway and automotive engineers recognize that under dynamic conditions there are:

1. A wide variation in the magnitude and frequency of individual loads on the pavement, in excess of static loads, caused by the vertical oscillation of the vehicle chassis and axle assemblies.

2. A redistribution of axle loads to the pavement caused by one or more of the following conditions (whose severity is a matter of interest to all concerned):

   a. Shifting of freight within the vehicle.

   b. Warpage of the vehicle caused by temperature differentials between its different portions.

   c. Forces set up within the vehicle as a result of sudden changes in horizontal, vertical, and rotational movements, or some combination of these movements.

   d. Changes in horizontal position of the tractor with respect to the trailer in trailer and semitrailer combinations.

3. Variations in dynamic axle loads due to the following vehicle design features:

   a. Spring suspension systems.

   b. Spacing and arrangement of axles, in single or tandem groups.

   c. Tandem axle mechanisms to equalize loads between axles.

   d. Sliding tandem and fifth wheels, dolly axles, adjustable axles, and spread tandems.

   e. Integrated tandems and independent tandems.

   f. Effect of tire-load transmission

Methods of Attacking the Problem

Two research approaches have been tried in determining the influence of those factors affecting the magnitude of dynamic axle load variations. One has involved experimental studies where dynamic axle load values were measured by various types of transducers, with various parameters varied (such as load, speed, suspension system, etc.) and the results recorded. The other approach has been analytical, based on a mathematical model of the dynamic problem.

Experimental Approach. Instrumentation to measure dynamic axle load changes as a vehicle travels over a road is of relatively recent origin. Prior to development of the strain gage and air pressure transducers and the electronic scale, quantitative measurements of this type were impossible. In 1953, Michigan first used strain gages mounted on an axle to monitor the dynamic effects of a truck passing over pavement. This instrumentation was improved in 1955 and 1956 bridge studies (1) where strain was measured outboard of the suspension system, thus reducing the mass undergoing accelerations not recorded by axle strain measurements. In October 1957, Hopkins and Boswell (2) reported on an instrumentation study where three methods of measuring dynamic axle loads were compared: 1) axle housing strain, 2) bulge or spread of tire sidewalls, and 3) changes in tire air pressure. These methods were evaluated by comparing the results with loads obtained as the instrumented truck traveled across an electronic scale. Cooperative tests were conducted by General Motors Proving Ground personnel and the Michigan State Highway Department in the Fall of 1957, to determine whether the air pressure or the strain gage method gave results correlating better with pavement deflection and strain. General Motors was using the first system and the Department the latter in determining dynamic axle load variations. As a result of these preliminary studies, a pilot truck was instrumented by the Highway Department in 1960 using differential pressure transducers on each set of dual rear wheels.

Analytical Approach. The Cornell Aeronautical Laboratory and Purdue University have confined their dynamic load research chiefly to the analytical approach. Under contract with the Bureau of Public Roads (3), in 1959 Cornell completed an analysis of basic problems involved in development of a comprehensive treatment of road loading mechanics, including development of a mathematical model of the vehicle and a discussion of model response to certain inputs. The Cornell report recommends that development of analytical models of highway vehicles be continued and that a program of experimental verification of these models be initiated. In 1963, Cornell published an analysis (4) of dynamic behavior of roads subject to longitudinally moving loads. A mathematical model of the road-subgrade structure was developed to establish the relative influences of dynamic and static loading on deflections and stresses induced by a vehicle in the pavement of a road structure.

Purdue's study of the same problem, under Professor Quinn's direction, also in cooperation with the Bureau of Public Roads (5), is basically an analytical approach, but includes an experimental study of vehicle characteristics. By combining the power spectrum of highway profile elevations with given vehicle characteristics, dynamic force power spectra may be obtained and also a probability density function of the dynamic force increment. In a more recent publication (6), Professor Quinn described how to obtain a pavement elevation power spectrum from dynamic tire force measurements. The power spectra from the two approaches are compared using different assumptions. Purdue's analytical approach has definite advantages, but should be substantiated by experimental means.

Road Surface Profile

The dynamic response of a vehicle can be related to the physical irregularity of the road surface. Such irregularities may be built into a pavement surface during construction or may develop normally with age, influenced in various ways by climatic conditions and normal traffic load.

Accurate road profiles will be needed as one major prerequisite in the attack on the dynamic load problem. It is desirable that the profile be a continuous record and essential that the measuring system not only pick up small vertical irregularities but also have the ability to measure the range of road wave lengths significant to vehicle ride.

For a long time the General Motors Research Laboratories have been working to develop such a road profilometer for rapid measurement of road profiles (7), known as the GMR Profilometer (Fig. 1). The Michigan State Highway Department in cooperation with the Bureau of Public Roads has built a duplicate model of the GMR Profilometer, which the Department proposes to try out on Michigan roads this year.

Fig. 2 illustrates a road profile measured by the GMR Profilometer at 40 mph in relation to a road as designed. The Department proposes to use its GMR Profilometer in the following manner to obtain the dynamic response of various vehicles over different types of pavement surfaces:

1. By means of the GMR Profilometer an analog profile of a road surface will be obtained on magnetic tape.

2. From this magnetic tape it will be possible to reproduce a profile trace on graph paper for visual observations.

Figure 1. The General Motors rapid travel profilometer.

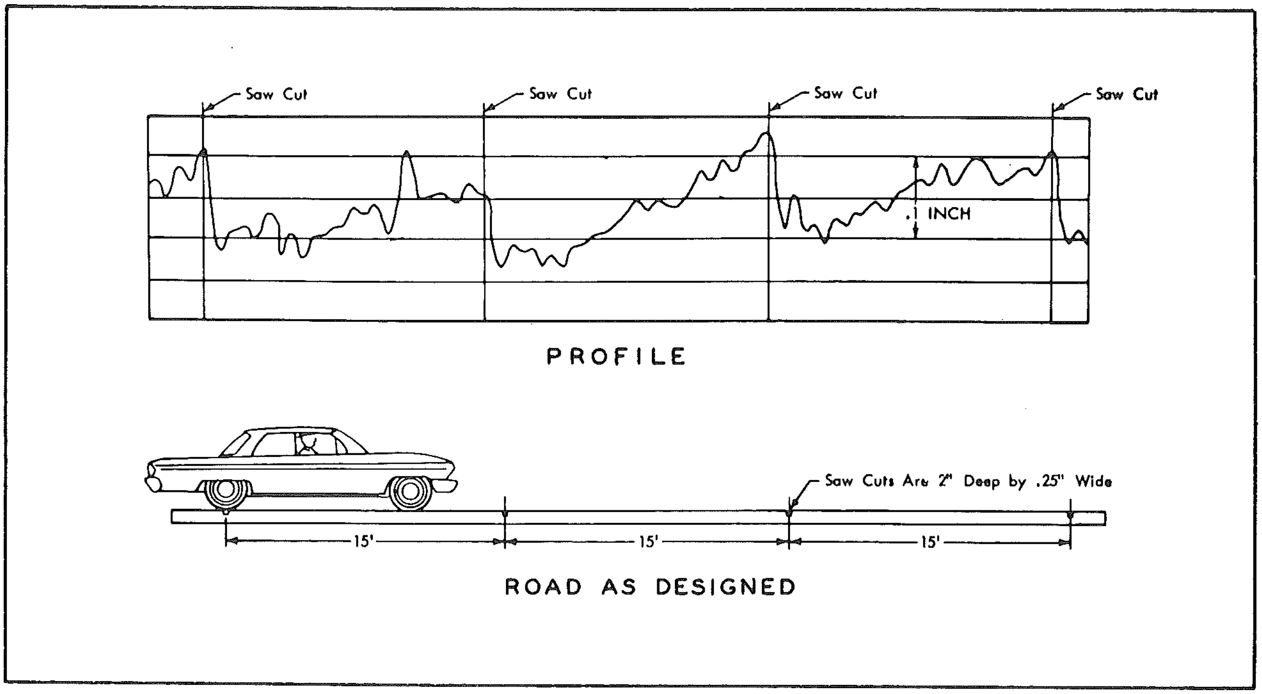


Figure 2. Road profile measured by GMR profilometer, in relation to the road as designed.

3. A numerical rating can be determined for any particular section of pavement in terms of roughness or rideability.

4. The magnetic tape profile will be used to determine the continuing force input to the pavement by a particular type of vehicle.

This can be done for a given vehicle by determining such constants as spring rate, damping coefficients, natural frequency, weight distribution, etc. Then these vehicle characteristics and the magnetic tape record of pavement profile can be mathematically combined to determine vehicle axle load variations while traveling over a particular pavement surface. By this method, it should be possible to solve the dynamic axle load problem in the laboratory with subsequent verification through dynamic field measurements, as proposed under a current Department research project concerning dynamic aspects of vehicles in relation to size and weight.

IMPACT LOADS CAUSED BY MOVING VEHICLES

The Department has been interested in determining the effects of dynamic loads on pavements and structures since 1944. Earlier studies, however, focused attention chiefly on the reaction of the pavement or bridge to dynamic effects, or impact. Generally these studies have indicated the response of the structure to a vehicle traveling at a certain speed with a known static load. Research in progress in cooperation with the Bureau of Public Roads is aimed at more comprehensive study of dynamic effects, their quantitative values under a variety of specific conditions, and study of variables influencing the magnitude of these effects. This investigation is compatible with, and a necessary adjunct to the studies recently completed at the AASHO Road Test by the Department of the Army, Purdue University, the Cornell Aeronautical Laboratory, and the Franklin Institute, as well as Michigan's study on "Automatic Weighing of Vehicles in Motion and Collection of Traffic Data by Electronic Methods," now in progress. This dynamic load study is one phase of a cooperative research project which the Department and the Automobile Manufacturers Association have been engaged in since 1956, and preliminary planning, instrumentation, and pilot testing have been completed.

Briefly, the investigation consists of a measurement program of the dynamic effects of a variety of truck types traveling at various speeds over rigid and flexible pavements having varying degrees of roughness.

This permits determination in survey form of the effects of vehicle speed, vehicle type-axle distribution, suspension systems, and pavement roughness. It will be a basis for more detailed and specific studies, under closer control, of these and additional parameters affecting the magnitude of impact.

The Department is considering using three possible methods of attack on the dynamic load problem:

1. Field testing commercial vehicles on various pavements using change in tire pressure to determine load on the pavement.

2. Use of an electronic scale installation to determine dynamic axle loads under controlled test conditions as suggested by Prof. Blythe.

3. By the road profile method, using the GMR Profilometer in the manner previously described.

Data from various Michigan pilot dynamic load studies will be used in the following text to illustrate the magnitude and frequency of dynamic loads that may be expected under normal operating conditions.

Wheel Load Variation with Speed

Fig. 3 presents the frequency of peak wheel loads above static values for a situation involving vehicle speeds of 20 and 40 mph, for a single axle load of 18,050 lb with all other conditions considered constant. The curves represent the number of load peaks per mile in each category of dynamic load increase over the static wheel load. The graph illustrates 1) how the peak load frequency varies with change in vehicle speed, and 2) how maximum impact load changes with speed. In other words, as speed increases, the magnitude of the peak loads tends to decrease but the maximum dynamic impact force increases. In this case, change in vehicle speed from 20 to 40 mph represented an increase in maximum impact load of approximately 1500 lb or 17 percent, the maximum impact forces above static load being respectively approximately 47 and 64 percent.

Wheel Load Variation with Pavement Condition

Fig. 4 illustrates the variation in dynamic left and right wheel loads on one axle carrying a static load of 18,050 lb and traveling at a speed of 40 mph over two types and conditions of road surfaces (a poor and rolling bituminous surface, and a poor concrete surface). The test covered 1250 ft of road surface. It is logical to expect that such variations in left and right wheel loads will be normal occurrences for all types of vehicles, due to many factors associated with vehicle response to changing road profile. The relative positioning of the curves in Fig. 4 indicates a shifting of the load from left to right or vice versa due perhaps to a rolling motion of the vehicle. Of importance is the fact that maximum impact loads occurred on the right wheel in both cases, amounting to 7500 lb or about 83 percent under Case 1 and 5750 lb or about 64 percent under Case 2.

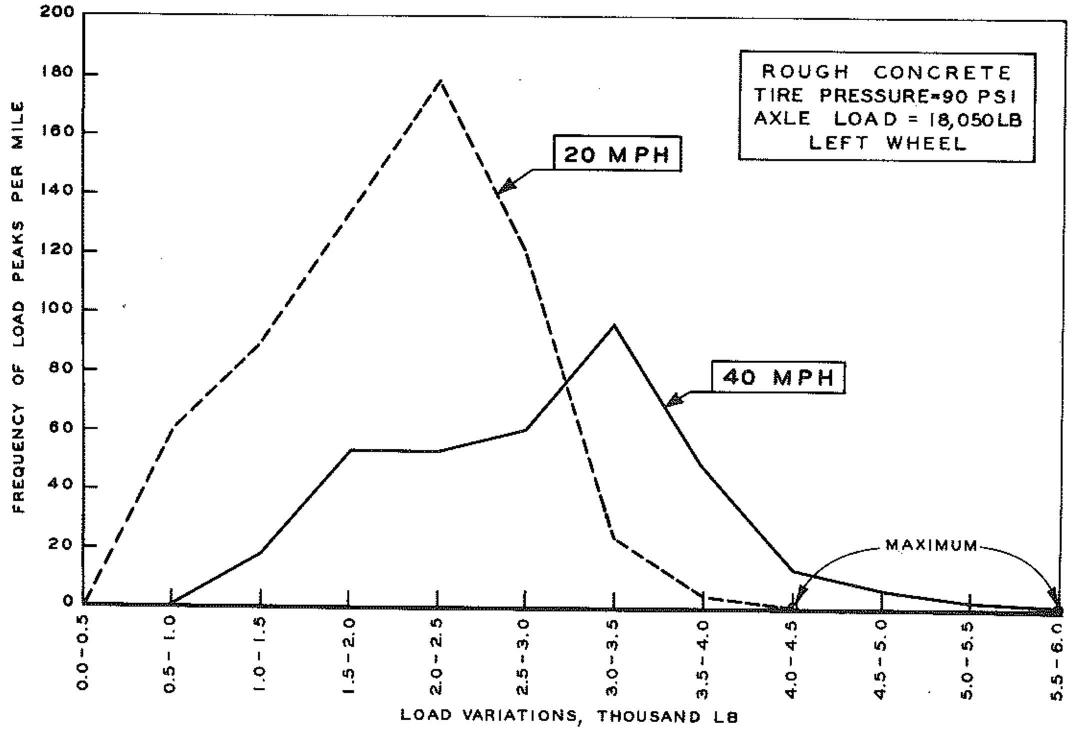
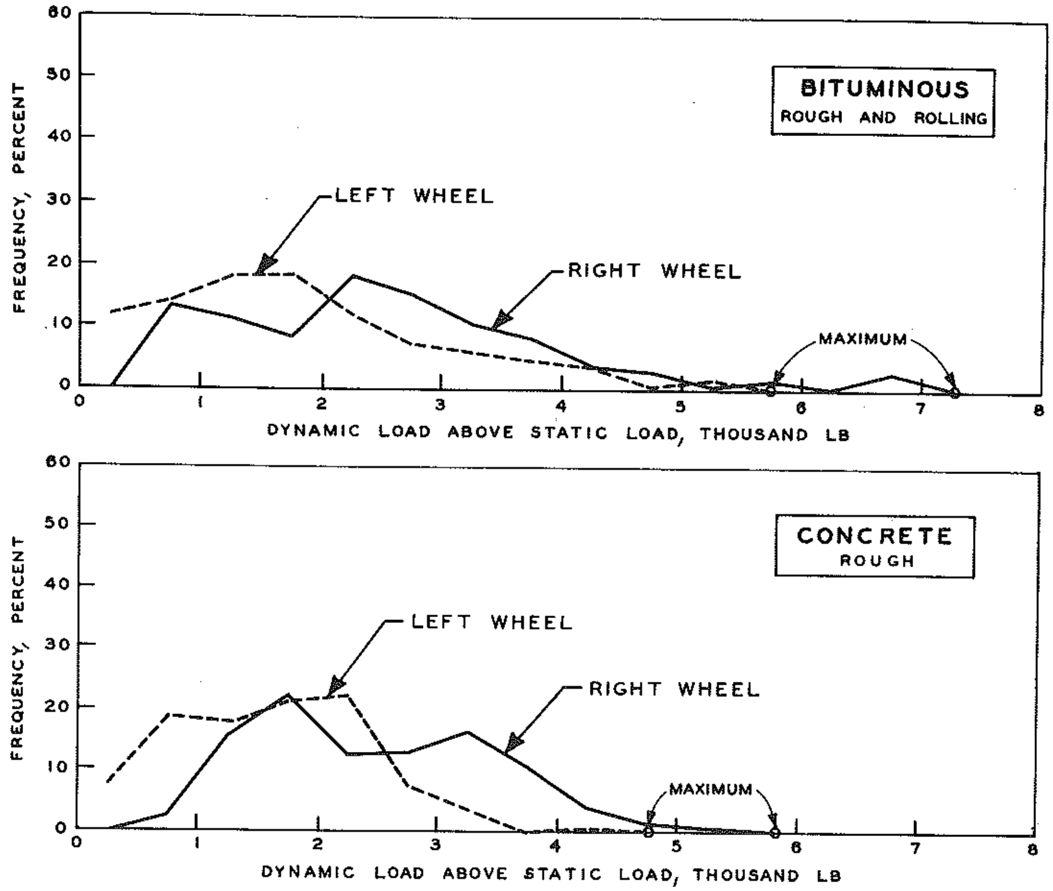


Figure 3. Single axle load variations at 20 and 40 mph.

Fig. 5 presents a relationship between maximum wheel load impact force and surface roughness in inches per mile as measured by the Michigan State Highway Department roughometer, similar in construction to the Bureau of Public Roads machine. The impact values in Fig. 5 are based on dynamic wheel loads obtained by a test vehicle operating over several different pavement surfaces of varying construction and degrees of roughness. Speed and tire pressure were constant at 40 mph and 70 psi respectively. The static axle load was 18,050 lb.



STATIC AXLE LOAD=18,050 LB - SPEED=40 MPH - TIRE PRESSURE= 70 PSI - 1/4 MILE TEST SECTION

Figure 4. Variation in wheel loads on one axle.

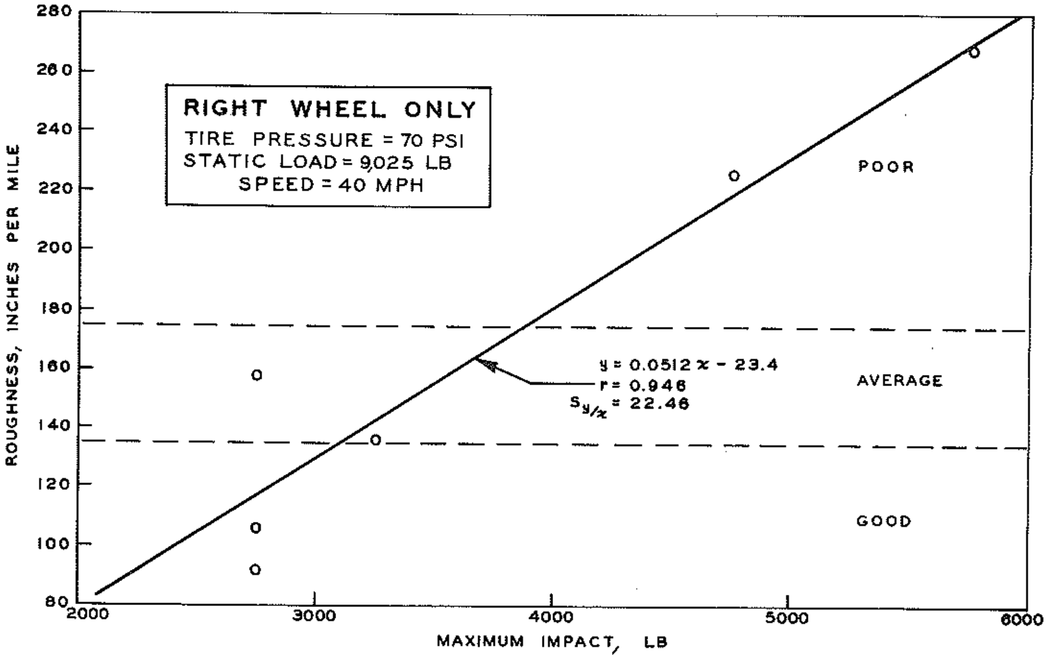


Figure 5. Maximum wheel load impact force in relation to pavement surface roughness.

Dynamic Axle Variations on Bridges

In 1957, the Department completed load deflection and vibration studies on several types of highway bridges (1). Tests were conducted with an instrumented test truck from which dynamic axle load variations were determined. The following results are extracted from that study:

The axle load variation was seldom more than ± 4 kips, except in the case of data from two bridges. One has had a very rough-riding surface since construction. Maximum axle load variation on this bridge was ± 6.8 kips on the mechanically sprung tractor axle, and ± 10.6 kips on the unsprung trailer axle. This departure from the static load is ± 44 and ± 58 percent, respectively. The other bridge had a bituminous surface on the approach pavement and a bump had formed near the north end of the bridge, causing a maximum axle load variation of ± 8.5 kips.

The bridge span with the largest percent impact as measured by dynamic bridge deflection was also the span on which greatest axle load variation occurred. In general the percent impact for the various spans appears to be reasonably consistent with the maximum percent axle load variation recorded while the truck was on the span (Fig. 6). However, six points fall farther away from the general pattern. Two of these points, representing low ratios of impact to axle load variation, are from a bridge that had relatively stiff simple spans. On the other hand, the four points representing high ratios were from two more flexible cantilever-type bridges.

Axle load variation increased in proportion to test truck speed. In Fig. 7, data from the tractor axle on one bridge are used to illustrate this correlation.

LOAD VARIATIONS DETERMINED BY MICHIGAN'S ELECTRONIC SCALES

The Michigan State Highway Department in cooperation with the Bureau of Public Roads has an electronic scale installation in operation at the Grass Lake weigh station on I 94 east of Jackson (Fig. 8). This installation is a system of four electronic scales with the electronic control and recording equipment necessary to obtain dynamic load data on each axle of a truck as it passes over each of four scales. It is possible to obtain quickly a representative quantity of dynamic axle load data from a variety of truck types. These data are recorded on magnetic tape, in a form for direct insertion into an electronic computer for analysis.

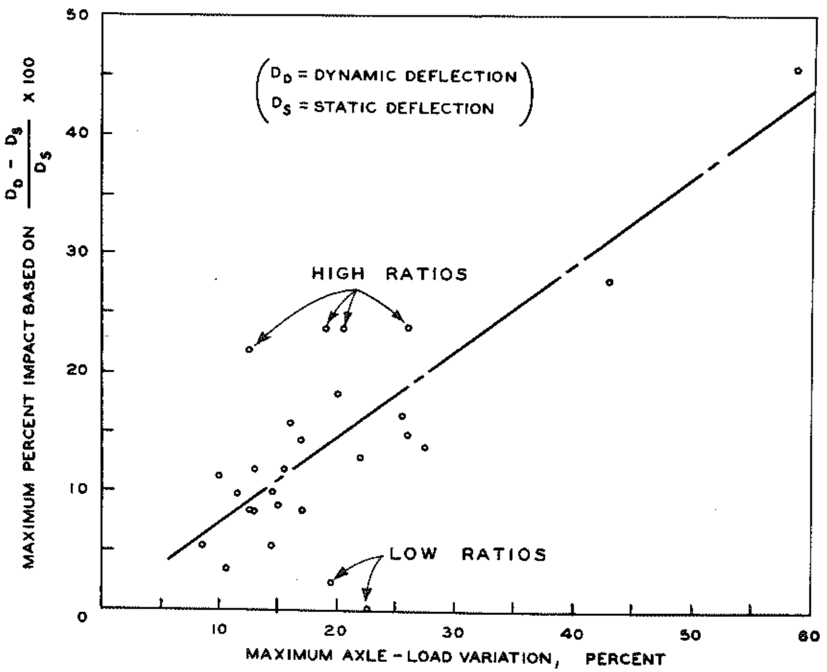


Figure 6. Maximum impact as measured by dynamic bridge deflection, compared with maximum axle-load variation for various bridge spans.

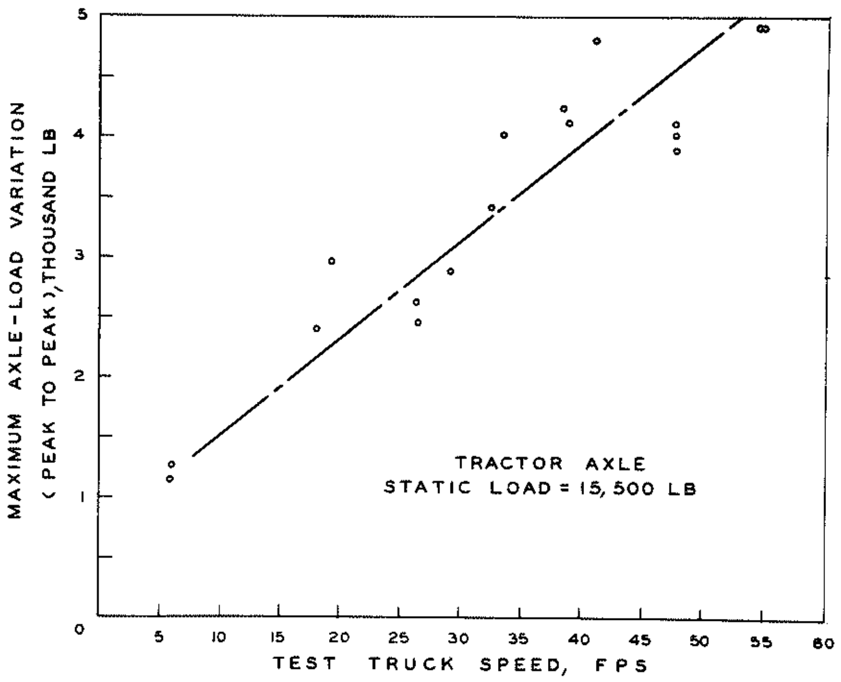


Figure 7. Maximum axle-load variation compared with test truck speed.

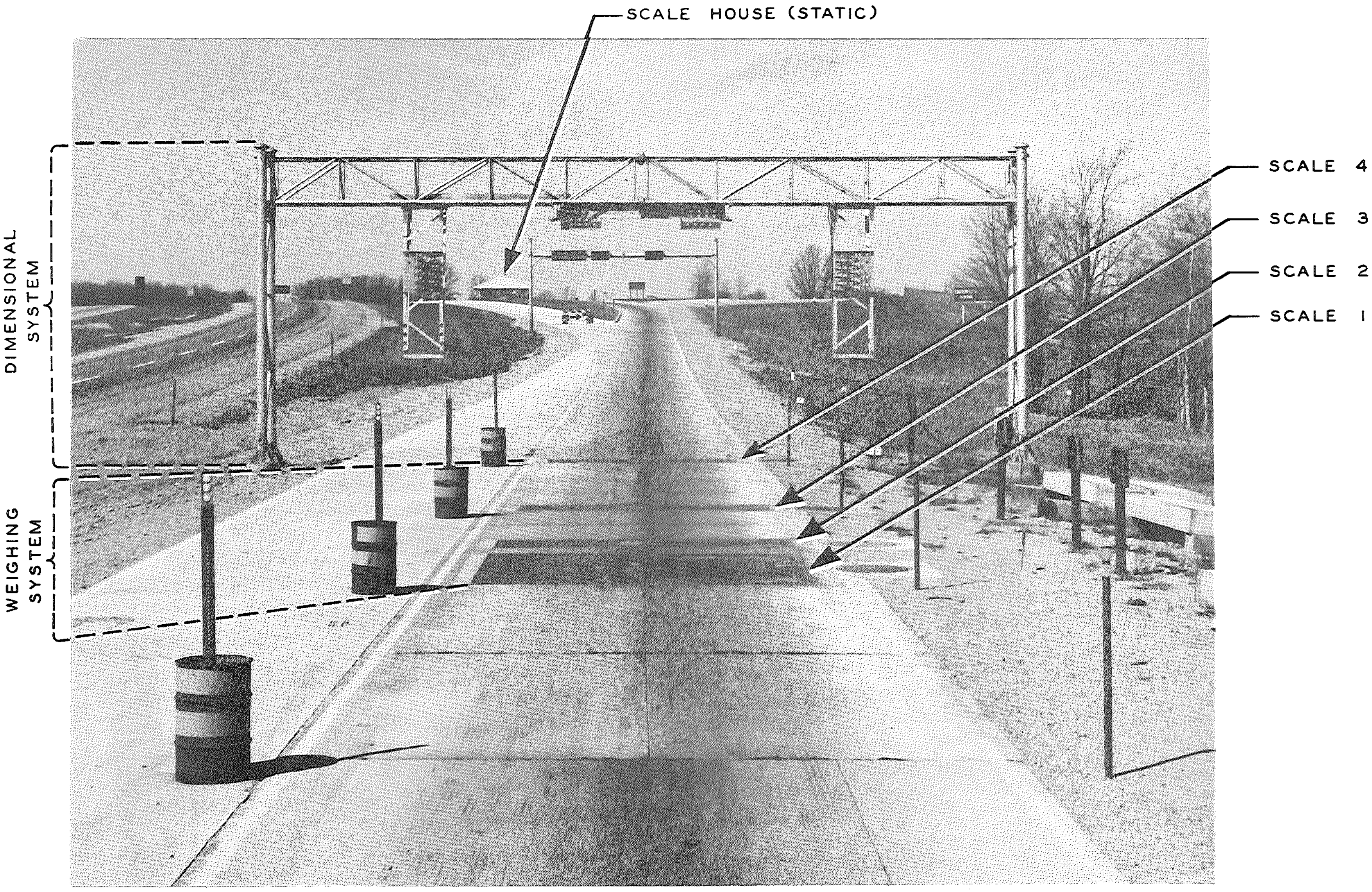


Figure 8. General view of Michigan experimental electronic scale project site.

Although the electronic scale system is one element in a complete automatic traffic data collecting station to be completed by the end of 1965, sufficient axle load weighings have been made to permit presentation of frequency and magnitude of dynamic axle load increments over the static axle weight under normal operating conditions.

The scale system layout is such that the dynamic transient response of a vehicle can be traced over a pavement distance of about 76 ft, as compared to one point on the pavement in the case of the Kentucky scale location. Fig. 9 shows the profile of the pavement ahead of the scales and in the area where the scales are located. As will be shown later, the slight rise ahead of the scales influences the manner in which the vehicle passes dynamically over the scales.

Fig. 10 shows the distribution of differences between static and dynamic loads for each scale and for a wide distribution of vehicle types normally found in the traffic stream, for single axles and for tandem axle groups. With reference to Fig. 9, the long wave starting some 220 ft ahead of Scale 1 causes a load buildup in the spring suspension system, which is released coming onto Scale 1 and causes Scale 1 to weigh heavy, Scale 2 light, Scale 3 heavy, and Scale 4 about normal. The wide distribution of axle loads is no doubt due to certain physical characteristics and to the speed of vehicles passing over the scale system. In the case of tandem axles, the distribution spread is more pronounced. The purpose of this demonstration is to show the nature of the impact forces that pavements receive from commercial vehicles in transit due to pavement profile irregularities and vehicle design characteristics.

Determining Vehicle Dynamic Characteristics

It is planned to use the Michigan electronic scale system to determine the dynamic characteristics of different types of trucks. This will supplement more elaborate procedures of instrumenting vehicles and driving them over various road surfaces at controlled speeds.

Fig. 11 shows portions of two analog traces taken for two types of vehicles as they passed over Scales 1 and 2 of the Michigan system. The top curve portrays the movement of the rear single axle on a 2S2-2 vehicle, and the bottom curve the rear axle of a 2S1 vehicle. In both cases, the graphs show how the magnitude and the frequency of dynamic axle load wave forms can be determined from a series of electronic scales in tandem. It should be possible by means of computer programming and analysis to convert such information into useful facts about the dynamic behavior of vehicle types.

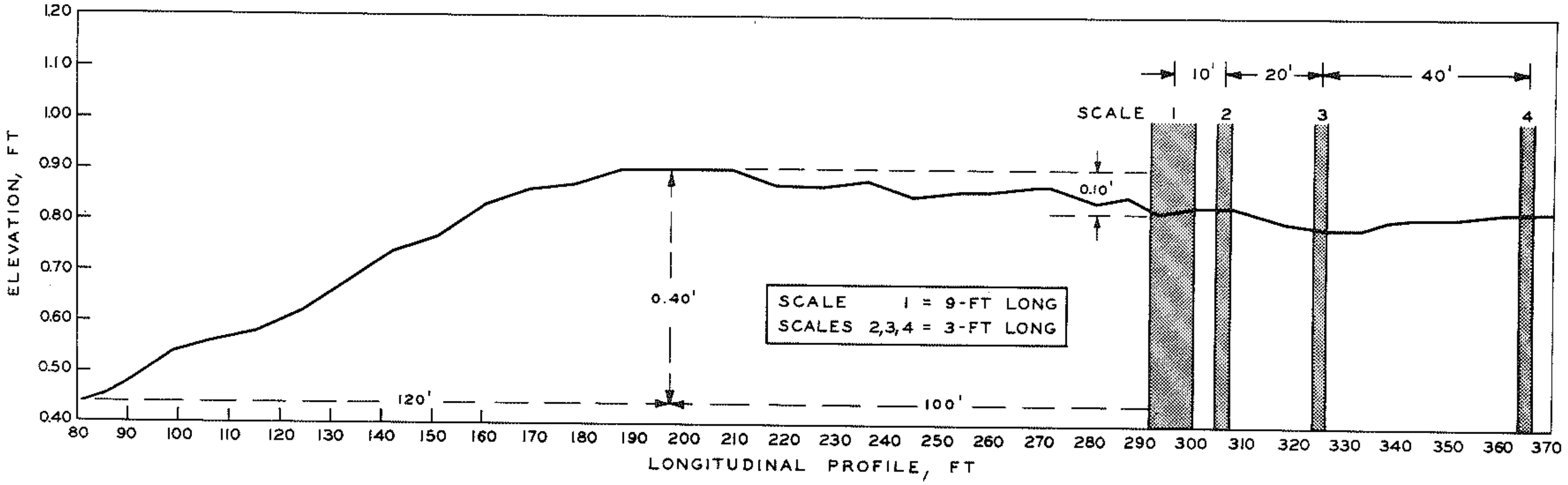


Figure 9. Pavement profile approaching scales and in scale area.

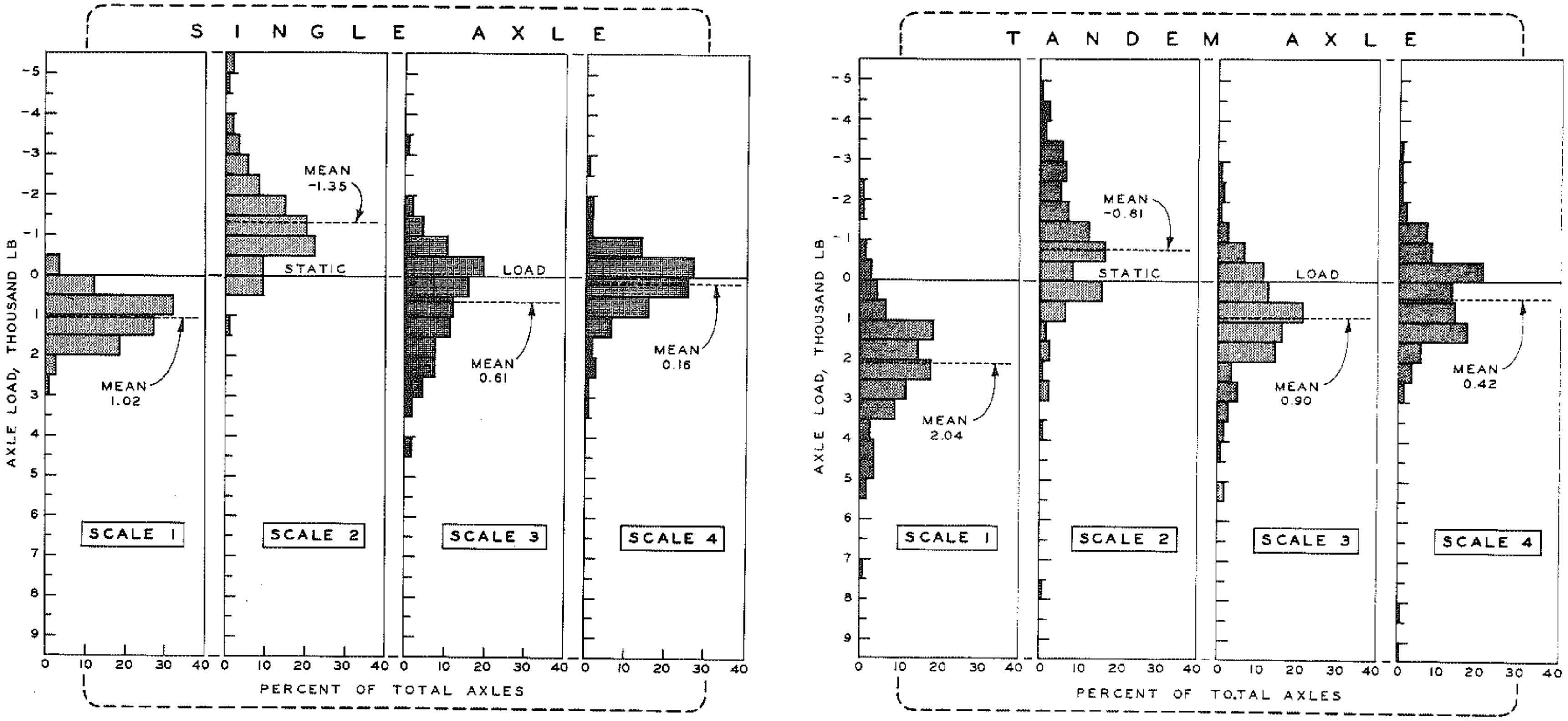


Figure 10. Distributions of differences between static and dynamic loads for each scale.

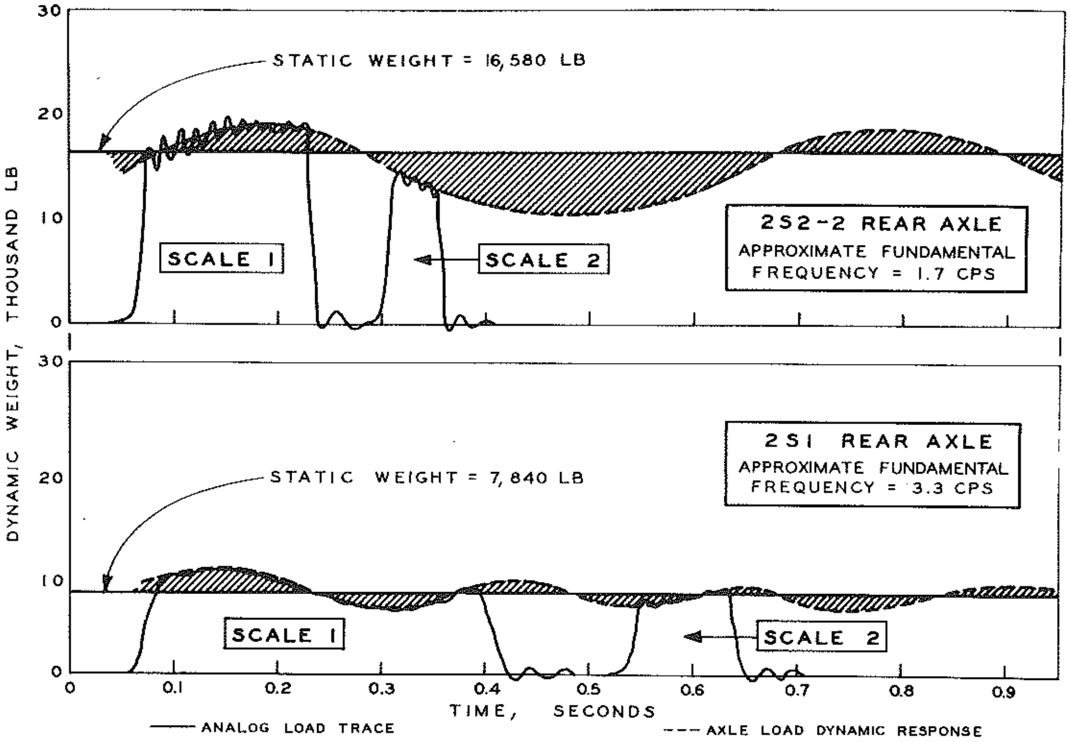


Figure 11. Analog load traces for rear axles of two types of vehicles.

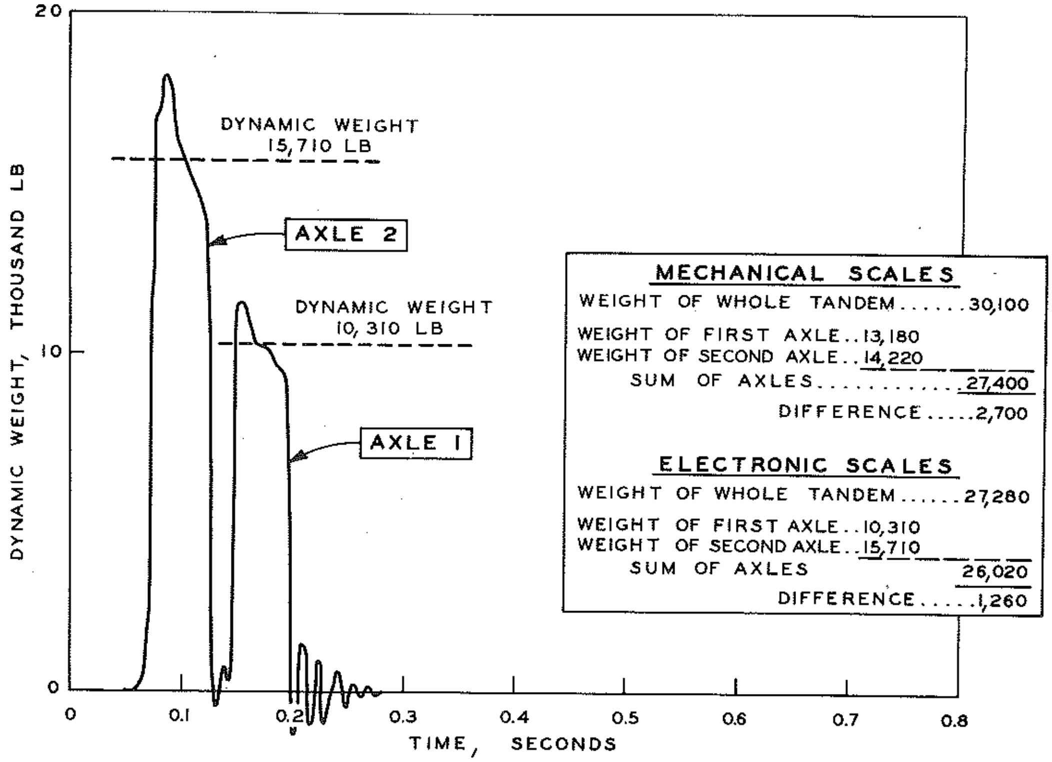


Figure 12. Analog load traces for a tandem axle group (first group of a 2S2-2 vehicle).

Distribution of Axle Loads in Tandem Groups

It is a well established fact that in many cases, the gross weight of a tandem axle with both axles on the scale will not equal the sum of the individual weighings of each axle in that group. The reasons for this are not generally understood. The difference between individual axles and the sum of axle weights and gross tandem weight may often exceed 1000 or even 2000 lb.

Fig. 12 illustrates a case in point, reproducing the analog load trace of a tandem axle passing over Scale 2 of the Michigan system. The graph clearly shows the difference in dynamic weights of individual axles of the tandem group. The difference in dynamic axle loads was 5400 lb. Weighing on the static scales, the sum of the individually weighed axles was 27,400 lb compared to the gross tandem weight of 30,100 lb, or a difference of 2700 lb. Similar electronic scale weights show a difference of only 1260 lb. As the Michigan study progresses this subject will be given the attention it deserves in light of the overall dynamic load problem.

CONCLUSIONS

1. Professor Blythe's statement that dynamic axle weights should be determined and accepted for consideration in establishing pavement design criteria is well founded. Michigan supports that concept, as illustrated by present research activities on the subject.

2. The Kentucky and Michigan studies indicate that electronic scale installations can be useful tools in determining dynamic axle loads and possibly other dynamic characteristics of vehicles.

3. Work to date indicates that the GMR Profilometer may also become a valuable device for correlating a road surface profile with vehicle dynamic response, thus providing a means of determining dynamic axle loads.

4. In order to verify dynamic load data obtained from analytical approaches, electronic scale installations, or the road profile method, it will be necessary to conduct field test programs with instrumented vehicles to determine dynamic axle load values for a wide range of pavement conditions and vehicle types.

REFERENCES

1. Oehler, L. T. "Vibration Susceptibilities of Various Bridge Types." ASCE Journal of the Structural Division, Vol. 83, No. ST4 (July 1957). Proc. Paper No. 1318.

2. Hopkins, R. C., and Boswell, H. H. "A Comparison of Methods Used for Measuring Variations in Loads Transferred Through Vehicle Tires to the Road Surface." Public Roads, Vol. 29, No. 10 (October 1957). pp. 221-26.

3. "Proposal for Research in Road Loading Mechanics." Buffalo: Cornell Aeronautical Laboratory, Inc. (October 21, 1958).

4. Thompson, W. E. "Analysis of Dynamic Behavior of Roads Subject to Longitudinally Moving Roads." Unpublished paper presented at 42nd Annual Meeting of the Highway Research Board (January 1963).

5. Quinn, B. E., and VanWyk, R. "A Method for Introducing Dynamic Vehicle Loads into the Design of Highways." HRB Proc, Vol. 40 (1961). pp. 111-24.

6. Quinn, B. E., and Zable, J. L. "Evaluating Highway Elevation Power Spectra from Vehicle Performance." Unpublished paper presented at 45th Annual Meeting of the Highway Research Board (January 1965).

7. Spangler, E. B., and Kelley, W. J. "GMR Road Profilometer: A Method for Measuring Road Profile." GM Corp. Research Publication GMR-452 (December 22, 1964).