Measuring Dynamic Vehicle Loads

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• The fifth objective of the AASHO Road Test was as follows: "To develop instrumentation, test procedures, data, graphs and formulas which will reflect the capabilities of the various test sections; and which will be helpful in future highway design in the evaluation of the load-carrying capabilities of existing highways and determining the most promising areas of further highway research."

It was with this objective in mind that development of equipment for measuring the dynamic load transmitted to the pavement and bridge structures through the tires of a moving vehicle was undertaken.

Past research and study has shown that the load transmitted through the tires of a vehicle in motion is not constant but varies in frequency and magnitude with many factors such as the pavement profile, vehicle speed, tire pressure, tire size and the vehicle suspension system. An adequate means of making a continuous record of the frequency and magnitude of these load variations was not available when the development reported herein was undertaken.

For many years studies of pavement deflections and slab strains were considered to be of value in determining the strength, design and future life of pavements; however, these measurements could only be determined under static load conditions or at best under creep speed load. It has long been observed that information on pavement behavior relating to loads applied by moving vehicles would be of value when compared to data collected under static load conditions. There are many other areas of highway and vehicle research and design where the relationship between dynamic load and other measurable characteristics would be of value, including bridge impact, loading due to pavement roughness, cracking, rutting and joints and the loads due to various vehicle suspension systems.

PREVIOUS RESEARCH

Dynamic loading is not a new concept. Results of methods and attempts to measure the phenomenon have been published for many years. These reports have covered many different methods of measuring the dynamic load change including the use of accelerometers, strain gages, load cells, tire bulging, photography, weighing systems and vertical displacements. All of the previous work has been partly successful and has pointed up the need for a more precise and usable method.

The pronounced difference in behavior of the flexible surface of the WASHO Road Test (HRB Special Report 22, 1955) in the outer and inner wheelpaths led to a special series of tests to determine the actual wheel loads, both static and dynamic, being transmitted to the pavement. Static measurements on a beam balance considering only the effect of load shift due to road crown were not significant and did not explain the observed pavement conditions. The effect of the crown caused a load shift of only 1 percent or less.

Two methods of measuring dynamic loads were tried. The first method of measuring the dynamic load utilized electric resistance strain gages bonded to the vehicle springs. The readings proved to be erratic but did indicate appreciable changes in the load being transmitted through the springs.

The second method utilized a special load cell which replaced the fifth wheel mounting brackets and rear trailer spring brackets. The strains were recorded on an oscillograph tape. The records showed considerable differential load change. The range of readings showed a load change of 400 lb at low speeds and 800 lb for higher speeds (30 mph) for wheel loads of 11,200 lb. The road surface on which the tests were conducted was considered to be smooth. The wide range of load change was contributed to the vehicle speed.

In 1954 the Bureau of Public Roads conducted extensive tests directed toward measuring dynamic loads. (*1*) In this study three methods of correlating load change as measured by an electronic scale to vehicle characteristics were reported. The three vehicle characteristics measured were strains on the axle housing, the bulge of the tire sidewall, and changes in the tire inflation pressure.

Measurements for all three methods were recorded as analog traces on a recording oscillograph and the vehicle weight was measured by the electronic scale. In this manner the vehicle weight could be compared to measurements of

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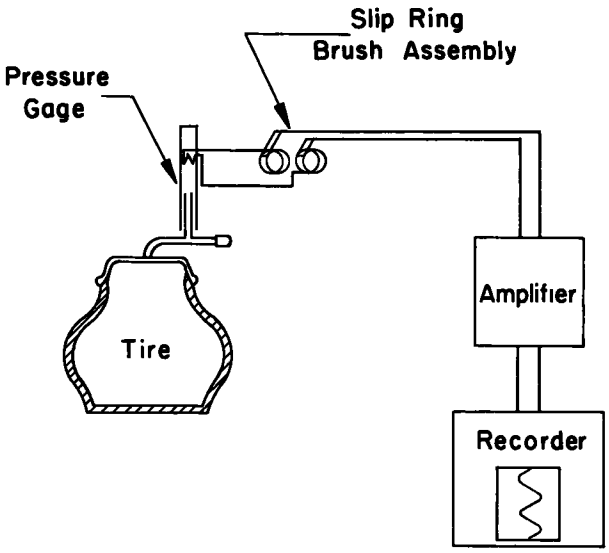

Figure 1. Schematic of BPR instrumentation.

vehicle characteristics. All methods gave compatible readings but each showed some degree of error.

It was concluded that the measurements of tire pressure change were the most practical and accurate method to use in future research.

DYNAMIC MEASURING SYSTEM

The tire pressure measuring equipment reported in the Bureau of Public Roads' study consisted of a pressure gage with a range from 0 to 50 psi. The pressure gage was fastened to the valve stem of the tire and revolved with the wheel. A slip-ring assembly was attached to an extension of the rear axle. The pressure recordings in the form of changes in electrical voltage across the strain gage were taken by the slip-ring assembly to a recording oscillograph. A schematic diagram of the equipment is shown in Figure 1. All recording equipment and the power supply were carried by the test vehicle. The main disadvantage of the system was measuring small pressure changes with a gage equal to the maximum tire inflation pressure.

The measuring system described hereafter was designed to overcome the shortcomings of the equipment used in the BPR study. The total tire inflation pressure was not recorded but rather the differential tire pressure existing between the vehicle tire and an air storage tank was measured. This allowed the use of a more sensitive pressure gage. The differential pressure gage had a range of 0 to ±1.5 psi. This was thought to be the limits of differential tire pressure due to normal changes in tire volume. The changes in pressure caused movement in a steel diaphragm which produced changes in voltage across a steel core induction coil. A cross-section of the gage is shown in Figure 2.

An extension of the tire valve stem was connected to a revolving joint which rotated with the wheel. The revolving joint was connected to the pressure gage. This eliminated the need for an electrical slip-ring assembly.

Figure 3 is a schematic of the measuring and recording systems. A bypass line around the differential pressure cell allowed the pressure to equalize before attempting to measure the pressure changes. Hence, the effects of temperature and leakage were minimized. When it was desirable to make a recording of differential pressure the solenoid valve was closed. Any change in pressure on the tire side of the gage would cause a corresponding movement in the pressure cell. The resulting electrical pressure changes were then amplified and recorded.

Several modifications were necessary as far as the physical makeup of the system was concerned. As much moisture as possible had to

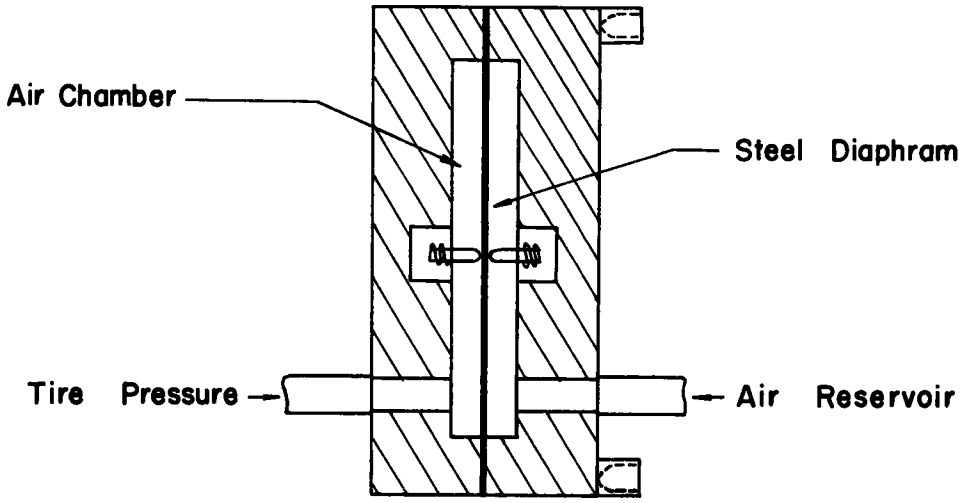

Figure 2. Cross-section of differential pressure cell.

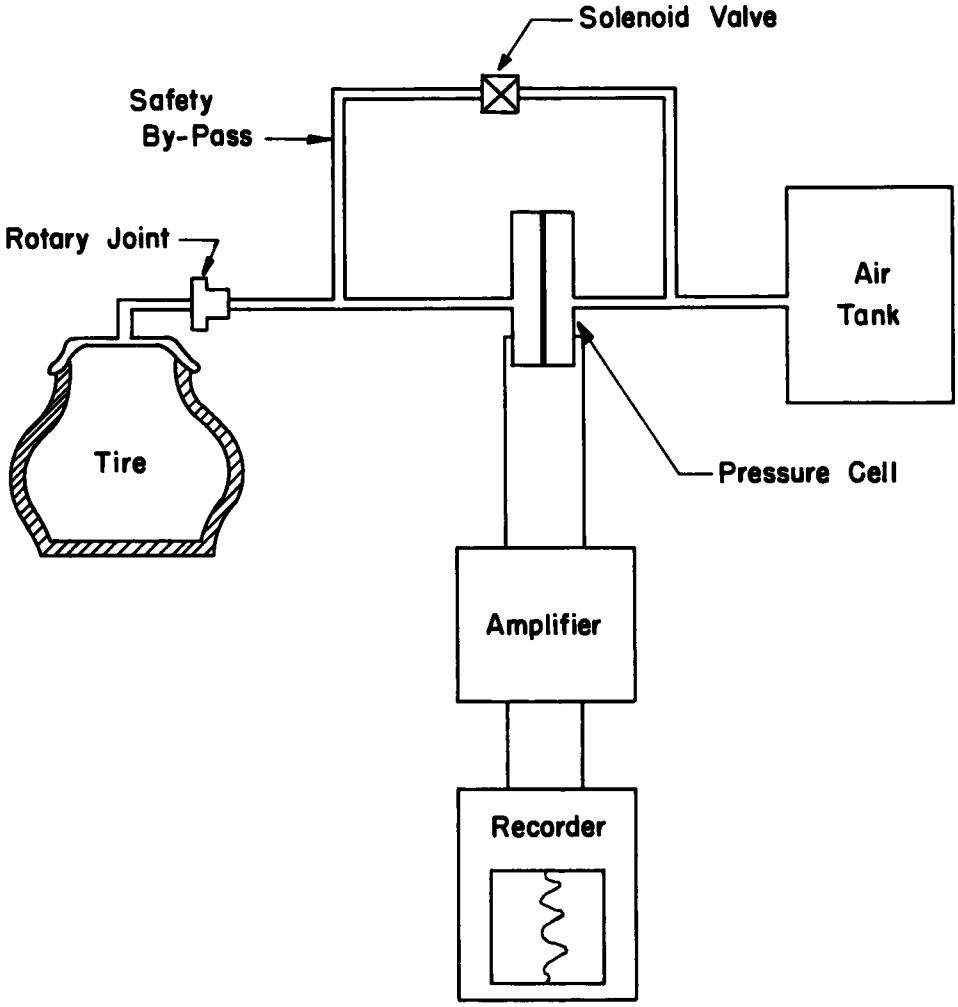

Figure 3. Schematic of AASHO Road Test instrumentation.

be removed from the system to prevent condensation in the air lines and pressure gages. The load on the rotary joint was reduced by relocating equipment in order to prevent excessive wear in the joint. In addition, the amount of rubber hose and copper tubing was minimized to prevent undesirable air losses.

The rotary joints were fastened to the steering axle as shown in Figure 4. A rubber hose from the pressure cell was connected to the rotary joint with a snap-on air chuck.

An easily removable frame held the rotary joint in place for the other wheels of the vehicle. The frame and rotary joint are shown in Figure 5. Both valve stems of the dual wheels were connected so that equal pressure was present in both tires. This fixture was readily adaptable to various truck wheels. The fixtures shown in Figures 4 and 5 could be moved from truck to truck with relative ease.

The differential pressure cell, a reservoir tank for one side of the cell, the solenoid valve, a gate valve and a junction box were all mounted on a portable plate (Fig. 6). By mounting this equipment on a plate which could be attached to the truck body, weight could be removed from the rotary joint and the pressure cell could be protected in case the mounting brackets were torn from the wheels while the vehicle was in motion. The pressure cell was protected from excessive differential pressures by the bypass system which remained open except when making pressure recordings. The entire system was protected by a mechanical gate valve. Figure 7 is a schematic of the support bracket and its attachments.

Figure 8 is a schematic of the final pneumatic system. Rubber hose connected the rotating joint to one side of the pressure cell. Copper tubing with sealed joints was used for all other connecting lines. Air chucks were provided at both ends of the rubber hose to allow rapid disconnection.

Figure 9 is a block diagram of the electrical system. The start-stop switch for the recording instruments was coupled with the solenoid valve

Figure 4. Rotary joint and mounting bracket for steering wheel.

switch. When the recorder was started the solenoid valve was simultaneously closed. When the recorder was stopped the solenoid valve was opened so that the pressure on either side of the differential pressure cell was equal. A bypass switch allowed the Philbrick amplifiers to be included or omitted from the system. They were used when greater sensitivity was desirable.

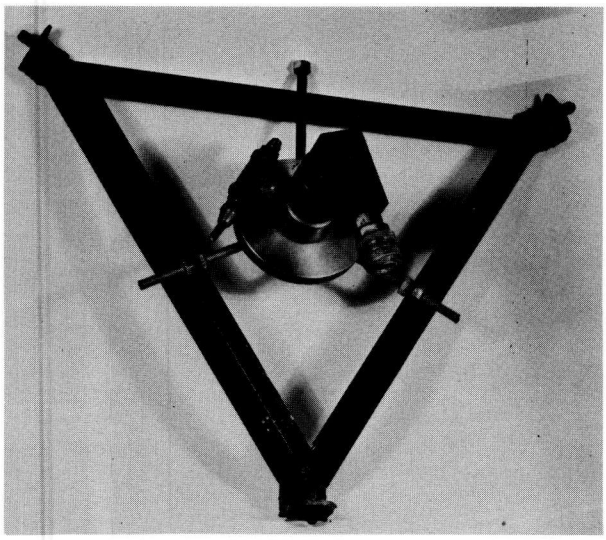

Figure 5. Rotary joint and mounting bracket for recessed rims.

CALIBRATION OF THE MEASURING SYSTEM

The need for calibrating the tire pressure equipment was shown clearly in the BPR study. In that study no real calibration was done. The continued development of electronic scales for measuring static and moving loads has facilitated the calibration procedures. The electronic scales available at the AASHO Road Test project measured the static load directly in pounds and the dynamic load in analog form on paper with known graduation.

A statistically valid test of the electronic scale was conducted to determine the degree of accuracy of weight measurements. It was

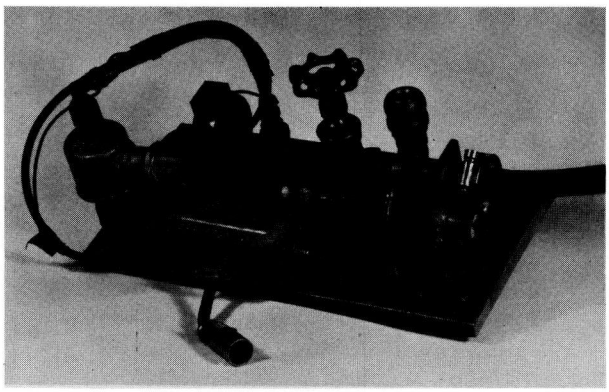

Figure 6. Transducer mounting bracket.

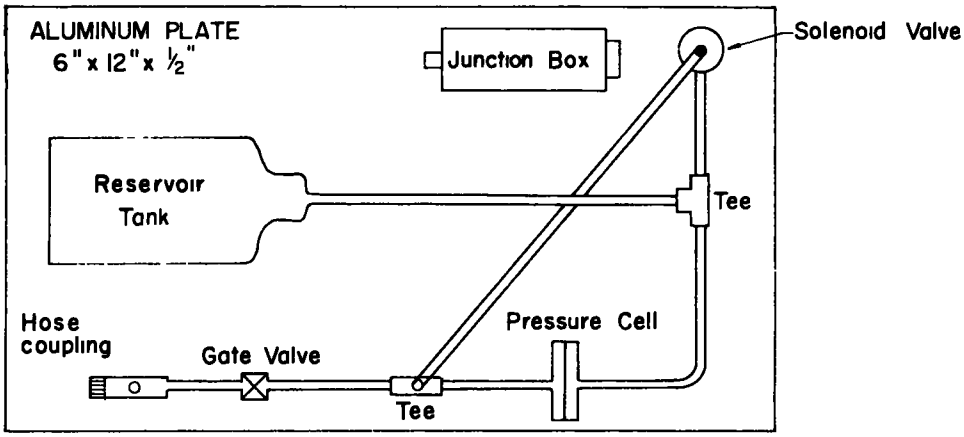

Figure 7. Schematic layout of transducer bracket.

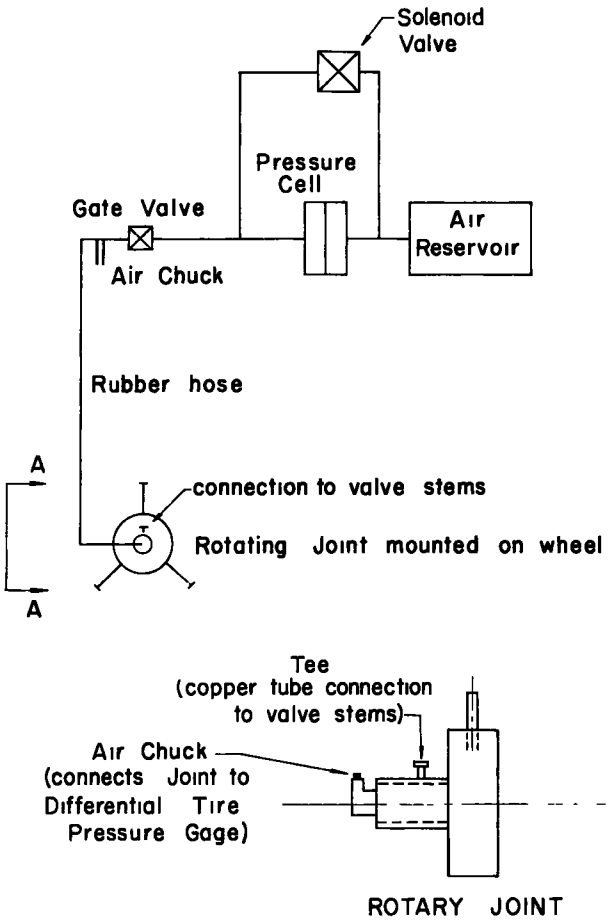

Figure 8. Schematic of pneumatic system.

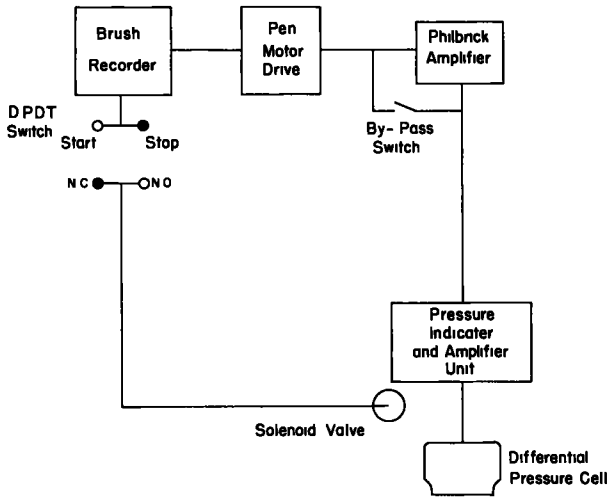

Figure 9. Block diagram of the electrical system.

found that the scale was correct to within 1 percent of the load weighed. This was approximately the accuracy of the electronic components which made up the recording equipment.

It was assumed that a vehicle moving along the pavements oscillates in the vertical and horizontal directions, the vertical direction being the major direction. The resultant of all oscillations of the vehicle frame, springs, and undercarriage is the vertical oscillation of the vehicle wheels as allowed by the pneumatic tires. It was further assumed that an artificially induced oscillation of the vehicle would be a valid facsimile of the actual vehicle oscillation.

Based on these assumptions a mechanical oscillator was utilized in the calibration work. This oscillator was electrically driven and mounted on a stiff welded frame of wide-flange beams. The oscillator was mounted on a vehicle and lashed in place during operation (Fig. 10). It consisted basically of identical eccentric rotors lying in the same vertical plane and turning at equal speeds in opposite directions.

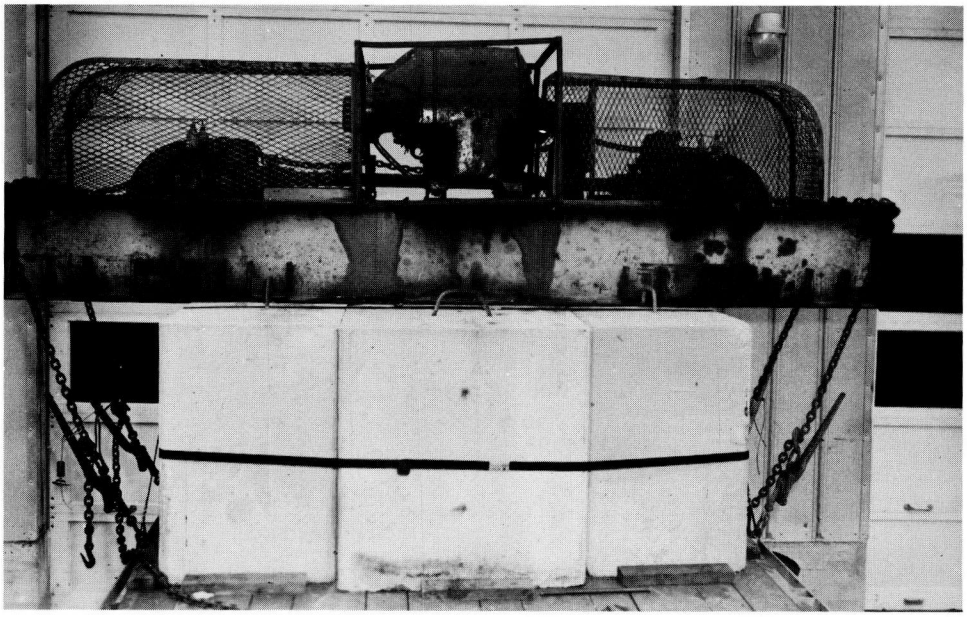

Figure 10. Mechanical oscillator mounted on truck.

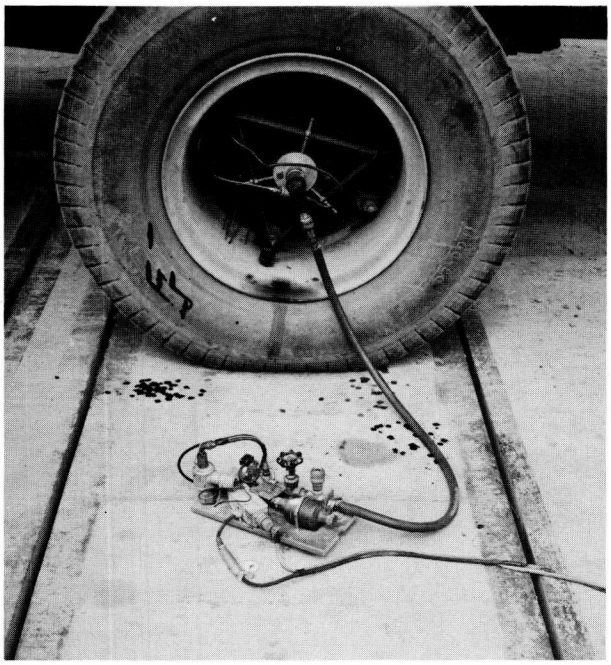

Figure 11. Transducer attached to tires.

Before attempting a dynamic calibration, the differential pressure gage and the electronic recording equipment were calibrated statically against known pressures such as a variable water column.

For calibration purposes one wheel was placed over the center of the scale platform, and the tire pressure recording equipment was attached to the wheel (Fig. 11).

The measurements of tire pressure changes were recorded as sinusoidal type waves by the recording equipment. The same result was produced on the dynamic recording electronic scale. Samples of these recordings are shown in Figure 12. This sample trace is an actual recording of load and differential tire pressure changes obtained during a calibration test.

The oscillator was run through a series of different frequency and mass combinations which excited the vehicle through a range of vertical oscillations. Recordings of load change and differential tire pressure change were made during all different oscillation conditions. From the recordings of load and differential pressure it was possible to determine the differential tire pressure load change relationship.

RESULTS OF CALIBRATION STUDIES

Under artificially induced oscillation the relationship between differential pressure change and the corresponding measured load change for any given tire, tire size, and tire inflation pressure was found to be linear. However, the slope of the load-differential pressure relationship is not constant for a given tire, but will vary with the inflation pressure (Fig. 13). As the tire inflation pressure increased, the slope of the load-differential pressure relationship also increased.

The effect of increased tire volume for a constant tire inflation pressure is shown in Figure 14. As the volume increases, the slope of the differential tire pressure-load relationship increases. Further experimentation is needed in order to determine the relationship of this volume effect.

Figure 15 shows the effect of varying the frequency of oscillation with a constant mass.

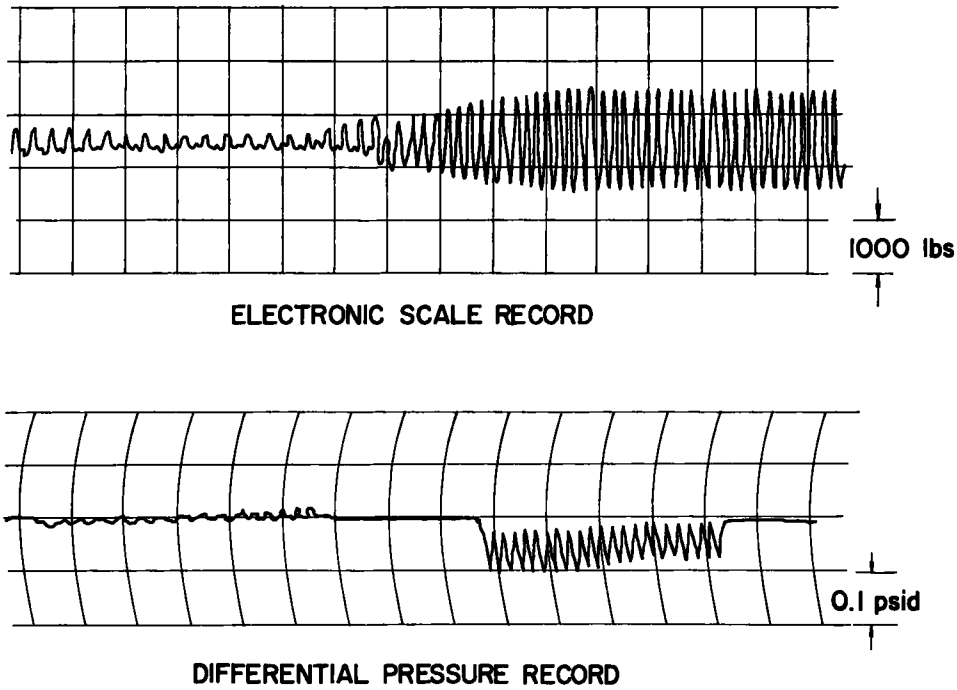

Figure 12. Response of transducer and scale.

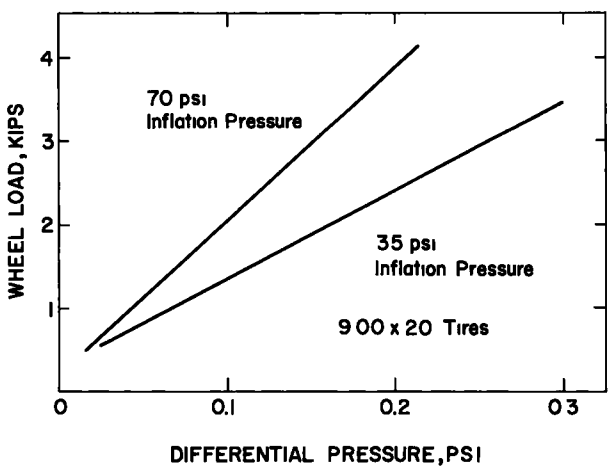

Figure 13. Effect of change in tire pressure.

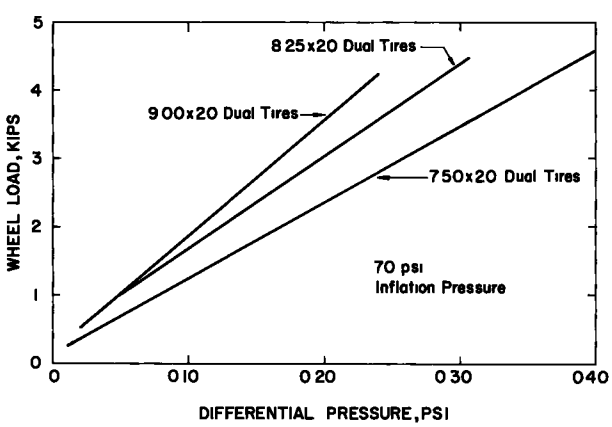

Figure 14. Effect of tire volume.

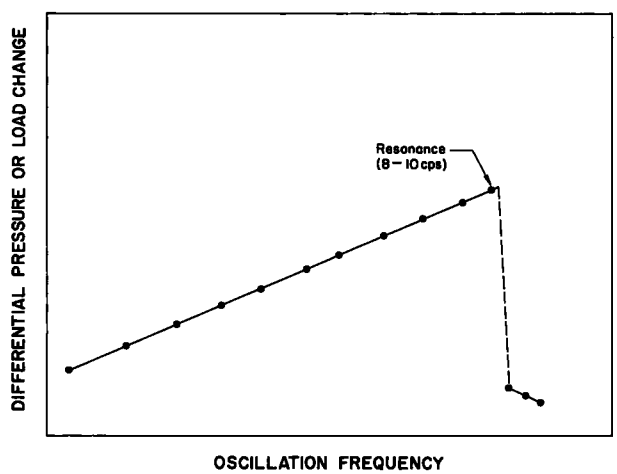

Figure 15. Relationship between differential changes and frequency.

As would be expected, an increase in frequency of oscillation increased both the differential tire pressure and load until the natural frequency of the vehicle suspension system was reached. At frequencies above the natural frequency of the vehicle, the differential tire pressure and load fall off very rapidly. Due to the mechanical features of the vehicles, it was impossible to oscillate the vehicle at frequencies higher than 8 to 10 cps.

Tests were conducted to determine the effects of various vehicle suspension systems on the differential pressure-load relationship. The study included vehicles with the spring system

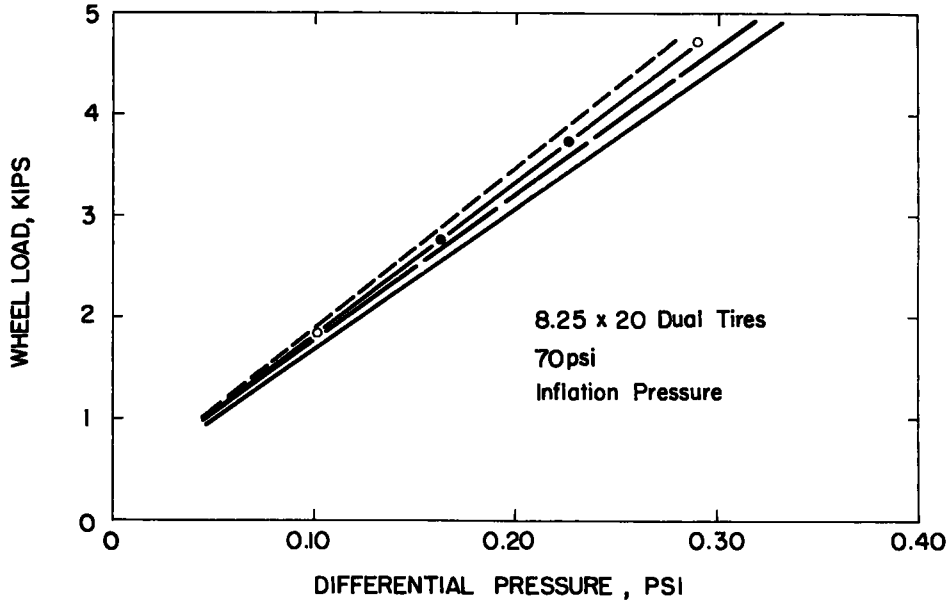

Figure 16. Variation between individual cells placed on the same tire.

blocked out to eliminate the suspension system altogether. There appeared to be no effect on the differential pressure-load relationship due to the various vehicle suspension systems.

A study was conducted to determine if there were significant differences in individual tires, size of tires, time of testing and the individual differential tire pressure gages and related recording equipment.

To determine the variability between the four individual tire pressure gages and associated recording equipment, a test was conducted whereby the tire pressure change-load change relationship was obtained for all four gages on all four wheels of a vehicle. Complete randomization of the order of measurements was utilized to insure unbiased results. The differential tire pressure-load relationship for each transducer system could be compared for each vehicle wheel and to other wheels of like volume. The variability between transducers placed on the same vehicle tire is shown in Figure 16. Significant differences existed between the four differential pressure gages and tires of like size and inflation pressure. It was also determined that the differential tire pressure-load relationships developed for a given tire by a given transducer did not show significant variation over an extended period of time. As a result of this study, calibration work proceeded using a specific set of recording instruments for each tire.

CORRELATION BETWEEN FIELD MEASUREMENTS AND CALIBRATION RESULTS

Efforts were made to determine the range of load change which could be expected in a moving vehicle by weighing a moving vehicle crossing the scale platform at various speeds. The shortness of the scale platform made a complete study of this type impractical for high speeds, as the random occurrence of peak values of load might require many hundreds of vehicle passages before they were obtained. In the limited study conducted, the range of load change encountered was approximately 33 percent of wheel load.

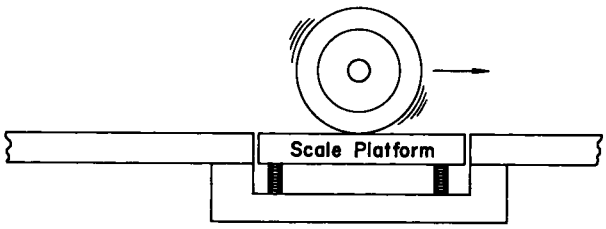

Figure 17. Schematic of rolling vehicle tests on scales.

An attempt was made to record the differential tire pressure at the same time the vehicle crossed the scale platform (Fig. 17). It was thought that this type of test would supply a reasonable check of the artificial oscillation calibration. A vehicle equipped with tire-pressure measuring instruments was driven over the scale platform. The corresponding differential pressure-load relationship was developed from the differential tire pressure and load recordings. The range covered by this relationship was not extensive as only low speeds could be used. The relationship developed did agree generally with the artificial oscillation calibration.

An effort was made to determine the differential tire pressure-load relationship when crossing obstructions of known size and shape

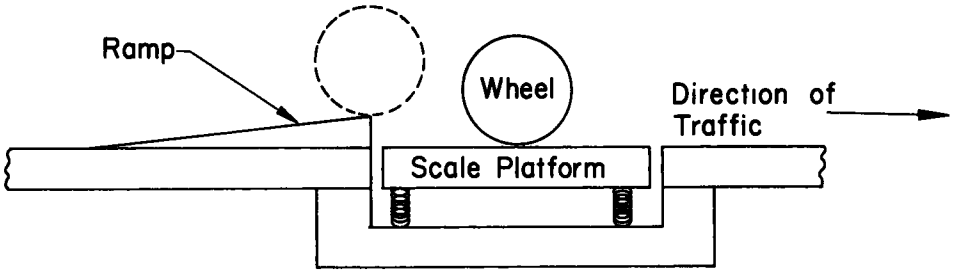

Figure 18. Schematic of drop test set-up.

at various speeds. Wood planks of varying thickness from ¾ to 2 in. were placed in the center of the scale platform and the vehicle driven across the scale at several speeds from creep speed to approximately 20 mph. Both differential tire pressure and load were measured. The experiment provided general agreement with the artificial calibration.

An effort was also made to determine the differential pressure-load relationship by recording the instantaneous impulse caused by dropping the tire onto the scale from several different heights. A series of ramps was constructed several feet in length, as wide as the tires and from ½ to 8 in. in height. The ramp was placed on the loading edge of the scale platform in such a position as to allow the wheel to land in the center of the scale platform when the vehicle was driven forward (Fig. 18).

The relationship developed was not identical with the artificial oscillation calibration. For low height ramps the two curves were nearly the same with the oscillation calibration curve showing greater load change for a given tire pressure change. When the higher ramps were used, the two curves diverged. The principal reason for the difference was probably the experimental procedure. When the tire rolls across the edge of the ramp, it becomes deformed and a tire pressure change is recorded. As the tire falls to the scale, the tire expands until the tire is larger than normal. When the tire strikes the scale platform it again deforms past the normal size to a size corresponding to the applied load. Hence the tire pressure change measured was larger than anticipated. This effect is more pronounced for the larger ramps as the tire is completely free during the fall from the higher ramps. Also, the recording instruments are not sensitive enough properly to determine applied load and differential pressure change at the high frequencies present in a test of this type.

APPLICATIONS OF THE DYNAMIC MEASURING SYSTEM

The differential tire pressure equipment was used to determine the variation of the force transmitted to several test pavements and test bridges on the AASHO Road Test.

Of special interest was the interaction between the vehicle-bridge systems upon passage of the test vehicle. The dynamic response of a bridge is dependent upon the vehicle frequency, damping characteristics of tires and springs and the magnitude of the variation of the interaction force. Hence, it was desirable to provide information that would provide some measure of the complex dynamic system that traversed the bridge.

Figure 19 shows typical records of the differential tire pressure and the corresponding response of the bridge. The test vehicle was a single-axle vehicle which had the springs blocked during passage over the bridge. This eliminated the uncertainty of the vehicle response due to the action of the springs by eliminating one of the major damping systems. Very good agreement was found between the vehicle and the bridge responses.

A principal limitation of the differential pressure measuring system is that the experimental data generated show only variations in the tire forces with respect to an unknown base, which is not necessarily equivalent to the static wheel loads. The recording instruments gave variations with respect to the ambient tire pressure at the instant the bypass valve around the pressure transducer was closed (Fig. 8). As the vehicle is normally in operation at that instant, the total pressure and resulting wheel loads are unknown.

CONCLUSIONS

1. Differential tire pressure measurements can be correlated with dynamic vehicle loads.
2. The relationship between differential tire pressure and load can be established by using a mechanical oscillator to produce controlled vehicle oscillations with corresponding load changes. These oscillations are a valid facsimile of actual vehicle movements which produce dynamic loads.
3. The relationship between differential pressure and load is reasonably linear.
4. The differential pressure-load relationship is affected by the tire pressure and the tire volume.

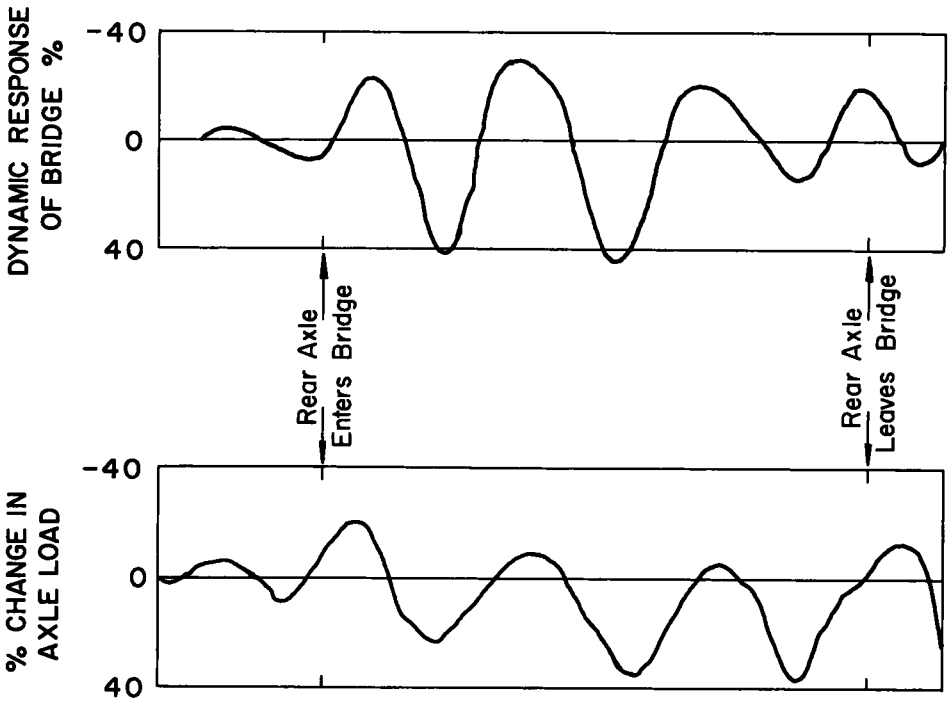

Figure 19. Dynamic response of bridge and test vehicle.

5. A usable instrument for measuring the dynamic response of vehicles has been developed. The use of the instrument extends to nearly every field where dynamic load measurements caused by pavement, vehicle or bridge characteristics are desired.

ACKNOWLEDGMENTS

These developments and studies were carried out as part of the research at the AASHO Road Test. The authors wish to acknowledge the contributions of all those who were connected with various phases of the investigation; particularly, W. Schwaderer, R. C. Leathers, and S. M. King during the course of developing the instrumentation.

REFERENCE

1. HOPKINS, R. C., AND BOSWELL, H. H., "Methods for Measuring Load Transfer Through Vehicle Tires to the Road Surface." *HRB Proc.*, 36: 240-252 (1957).

DISCUSSION

Evan Gardner, Pennsylvania Department of Highways.—Was any attempt made to correlate this tire pressure device with the profilometer? More specifically, could this be used as a profilometer for the serviceability rating?

Fisher.—No studies were conducted that would indicate a correlation between the profilometer and tire pressure. Perhaps Mr. Carey would have a comment he could offer at this point.

Carey.—The instrument in its present state would not do because there is a drift in tire pressure caused by changes in temperature. Only short runs could be made. We did not attempt this correlation.

Fisher.—One thing to keep in mind is that in this type of measuring system a drift is inherent. Hence, when measuring dynamic load changes it is difficult to establish the base around which the load change is occurring. It is necessary to assume that the oscillation is around the static load level. From an oscillation as shown in Figure 19 only the dynamic change recorded any instant of time is known. This is not the total load. The total load is obtained by adding the static load and the dynamic change.

J. B. Bidwell, General Motors Research.—What was the band width of this measuring system? With the long tube connecting the gage to the tire I would expect considerable attenuation at reasonably high frequencies which I am sure exist. In case of trucks I do not recall what real high frequencies might be.

In the case of passenger cars they are at least in the order of 10 cps, so you want a band width at least beyond that. For trucks it is probably as high as 20 or 30 cps. If you knew the dynamic characteristics of the vehicle you could use this load change to compute what the road profile would be. However, the road profile and the load would not directly correlate without inserting this additional dynamic system in between them. It does not look to me as if it would be a very good way of measuring road profile.

Fisher.—The major calibration range was in frequencies up to about 8 or 12 cps. As far as we could determine there was not a great amount of influence during normal test runs of the secondary frequencies (tire hop frequency). The major frequency oscillations are relatively low in magnitude, probably 3 or 4 cps.

M. E. DeReus, Missouri State Highway Department.—An impact factor of 20 percent has previously been recommended for use in design formulas for rigid pavement. From the results of your measurements do you think this is a good figure?

F. H. Scrivner, Texas Transportation Institute.—I should think so. However, we have made many studies of the strain in the edge of the pavement as related to speed similar to some of the work that was done on flexible pavement that was described in a previous paper. We always found that with increased speed the strain in the pavement was reduced. There seems to be some conflict between the data from a continually vibrating load that would presumably increase with roughness of pavement, or with speed, and yet we measure smaller strains as the speed is increased. Now this a question that still has to be resolved.

Fisher.—When we consider the dynamic strain measurements that were made in many cases on the Test Road, the probability factor must be considered because the gages were at finite locations and the probability of having the major component at that instance of time must be considered in the problem.

S. M. Fergus, Standard Oil Company of Ohio.—I do not think it was mentioned in the paper. What is the amount of the impact load? What was the maximum amount? I mean the wheel load is in pounds and the impact force is also in pounds. What was found to be the relation between these as far as maximum is concerned? Where you drop the load ½ in. or less, you measure the force. How much was it in relation to the wheel load?

Fisher.—The dynamic force due to the drop tests was very erratic. In addition, experimental procedures caused complications in measuring the total change. The wheel loads considered were of the order of 6,000 lb. I think the dynamic increment is reported in AASHO Road Test Report 6. It would depend on the type of damping system. In the system where we had the springs blocked out we had changes of 40 percent in the wheel loads. Thus, the impact load could be 140 percent of the static load or even higher.

F. N. Finn, The Asphalt Institute.—I would like to interject a word of caution relative to the effect of dynamic loads on highways. Mr. Fisher has clearly demonstrated that vehicles transmit variable loads to a pavement or bridge structure due to characteristics of the vehicle and its load. He has shown, for bridges, a good correspondence between the dynamic load and the stress-strain measurements on the bridge. However, for a pavement we must consider the inertia of the mass of material which is affected in order for a pavement to deflect. In a paper for the Association of Asphalt Paving Technologists in 1943,* Mr. V. A. Endersby pointed out that conceivably some 50,000 tons of material could be set in motion in order to deflect a pavement. Considerations of dynamics must include a study of pavement response similar to the work presented here relative to bridge response.

* Endersby, V. A., "The Bearing Power of Roads and Airports." *Proc. AAPT*, Vol. 15 (December 1943).