DYNAMIC LOAD ASPECTS OF
TRUCK SIZE AND WEIGHT

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MICHIGAN DEPARTMENT OF STATE HIGHWAYS

DYNAMIC LOAD ASPECTS OF TRUCK SIZE AND WEIGHT

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ABSTRACT

This study, performed in cooperation with the Federal Highway Administration had two goals: 1) Find an effective force transducer to measure vehicle induced dynamic loads, and 2) Perform a dynamic force survey for various trucks and highway types. Tire air pressure variation was selected as a measure of force since calibrated tires would facilitate large scale dynamic force surveys. Difficulty in developing this transducer led to concentration of the study toward this major goal.

Two major problems were successfully solved. 1) Development of a vital bypass filter system which permitted use of highly sensitive differential pressure cells, and 2) Development of methods to instrument trucks with accelerometers and strain gages to sense actual force for calibration of the tires. Transducer development led to two significant discoveries: 1) adiabatic conditions must be maintained during calibration of the tire, and 2) the pressure cell bypass filter must be at standard tire pressure when setting the time constant. A typical automotive test tire was successfully calibrated and work proceeded to calibration of truck-size tires. Complex computer programs were developed to aid the calibration procedure and favorable results were obtained.

INTRODUCTION

Dynamic loads on pavements and structures have been a subject of interest to this Department since 1944. From 1956 to 1963 the Department, in cooperation with the Automobile Manufacturers Association, performed preliminary planning, instrumentation and pilot studies directed toward a comprehensive dynamic load study. In July 1964 this Department began work on the project in cooperation with the Federal Highway Administration as a Highway Planning and Research Study. The original proposal contained five objectives:

1) Obtain the actual dynamic force signal.
2) Determine the relationship between dynamic force and road profile.
3) Find the influence of speed on dynamic force.
4) Determine the effect of vehicle characteristics on dynamic force.
5) Determine the dynamic forces due to vehicle pitch and roll components.

The study was separated into four phases.

A) A preliminary study using an electronic scale to obtain limited dynamic data from a few trucks, test some theoretical approaches, and calibrate tire air pressure instrumentation.

B) Use the calibrated tire air pressure instrumentation to do a large scale dynamic force survey of commercial vehicles.

C) Use two typical, instrumented trucks to obtain dynamic force data from a variety of roads.

D) Analyze the data and present findings.

Due to the concentration of efforts on competing HPR projects, progress during the original two year schedule was limited to pre-test planning, procurement, design of instrumentation and development of data processing methods and equipment. In addition, preliminary tests revealed several difficulties in using the vehicle tire as a force transducer. An extension to 1968 allowed the project to continue, incorporating a modified research procedure that included detailed analysis of the tire as transducer. Four phases were proposed:

A) Evaluate the tire as a force transducer for a simple, auto sized test suspension system similar to that of the BPR Roughometer. If negative results occur for this simple system, abandon the tire transducer concept.

B) If successful in Phase A, develop a method to calibrate a truck sized tire.

C) Develop large scale analog-to-digital methods of data handling.

D) Conduct a field study using calibrated tires on specific test vehicles, operating at various speeds and over various pavement types and levels of roughness.

Phases A and C were successfully completed. Phase B, the most crucial, was essentially completed and as the report shows, was nominally successful. Phase D could not be completed since it required complete finalization of Phase B.

During the latter portion of this study, General Motors Corporation developed an instrumented wheel force transducer that provided excellent dynamic force data and this development could have justified termination of the Michigan study. It was felt however, that work should continue on the tire transducer for four reasons;

1) The tire transducer is much less expensive than an instrumented wheel.
2) Instrumentation for the tire is much simpler, involving no strain gages or special electronics.
3) It would be less difficult to transfer calibrated tires from vehicle to vehicle during large scale truck-road studies.
4) Simultaneous output from several tires would be more economical considering the low cost per tire.

Most of the fruitful work on this project occurred during the extension period from 1966 to 1968 and extending up to the present time. The report therefore, will briefly cover early results and then concentrate on Phases A and B of the modified research program proposed for the time extension. Phase A was completed as mentioned earlier and indicates that tire air pressure changes can be related to dynamic force. Phase B indicates strongly that results of Phase A will hold for truck sized tires.

EARLY RESEARCH

Although all of the objectives of this project have not been completely satisfied, this report is presented as a final document on the study. The primary goal or hypothesis - that a vehicle tire would be used as a transducer for dynamic tire-pavement interface force - has been demonstrated as feasible and practical. Most of the difficulties encountered in the work were either overcome or circumvented by the techniques detailed later in this report. The study's principal value for future workers concerned with dynamic pavement and bridge loadings, will lie in the economical, validated force transducer and its method of use.

Vehicle Instrumentation

Instrumentation to sense dynamic force was the first consideration of all original investigations in this field. An early report by Hopkins and Boswell (1) led the General Motors Corporation to evaluate tire air pres-

axle housing strain as a method of reading dynamic force. Accordingly, the Department fitted out a heavy, two-axle truck with strain gages on the rear axle housing. While this work was underway, General Motors obtained results that favored tire pressure changes as a measure of force. This prompted the Department to study both methods by adding differential air pressure cells to the test vehicle.

Progress to this point revealed three major difficulties with instrumented axles that added further impetus to development of a wheel transducer of some sort. These difficulties were:

1) Strain gages are difficult and expensive to install on large-truck axle housings. This could make dynamic force surveys with a number of trucks prohibitively expensive.

2) The asymmetrical geometry of most axle housings leads to contamination of the vertical force data with torque and shear components. Locating the gages to minimize these unwanted components proved to be difficult and time consuming.

3) The strain gages cannot sense contributions to dynamic force due to acceleration of mass outside the gage location. This mass is composed of a portion of the axle housing, a portion of the spring, and the entire wheel assembly including tires, rim and brakes. Accelerometers could sense accelerations of the outside mass, from which force could be derived, but the process is complex and requires the disassembly and weighing of the

axle to be instrumented. This would greatly impede the use of instrumented axles for general dynamic force surveys.

The difficulties with instrumented axles and a desire to do large scale surveys led to a decision at this time to concentrate on the tire as a transducer. Consequently the instrumented axle was viewed only as an aid in calibrating the tire transducer. It was also decided that accelerometer correction would be added only if the instrumented axle was used for tire calibration. Efforts were then directed toward use of the tire as a force transducer by measuring instantaneous changes in pressure with the differential pressure cell.

The Differential Pressure Cell

Changes in tire pressure due to dynamic loading are relatively small, with peak pressures seldom more than 0.75 psi. For this reason, an absolute pressure transducer could not be used to monitor tire pressure. A pressure transducer able to handle typical tire pressures of 70 to 90 psi would be insensitive to small pressure changes. The problem was solved by use of a differential pressure cell which senses the difference in pressure between its front and rear inlets. The cell consists of a small metal chamber with inlets at both ends. The output is provided by strain gages bonded to a flexible diaphragm which blocks passage of air through the chamber. Typical cells have a range of $\pm$ 1.5 psi and a flat response from 0 to 1,000 cps.

Air pressure signals from a moving tire can be regarded as a high level "d. c." component of 70 to 90 psi and a varying, low level "a. c." component. The differential pressure cell can be used to monitor tire pressures by feeding the "d. c." component into one inlet and the "d. c." plus "a. c." components into the other. The "d. c." components will then cancel leaving only the desired "a. c." component. In practice this requires a pressure bypass line that connects one inlet to the other through a filtering device that passes only the "d. c." component. This filtering device can be properly thought of as a signal filter that passes only very low frequencies (Fig. 1). Initially, the bypass line was fitted with a simple shut-off valve. Pressures around the cell were equalized at the start of a run by opening the valve and then closing it to block the "a. c." component. This proved to be unworkable, however, because rising temperatures in the tire during a run rapidly increased the average tire pressure driving the pressure cell signal off-scale. It was thought that this "baseline drift" could be stopped by installation of a bleed valve in the bypass line that would pass low frequency pressure drifts but still block the "a. c." components of interest.

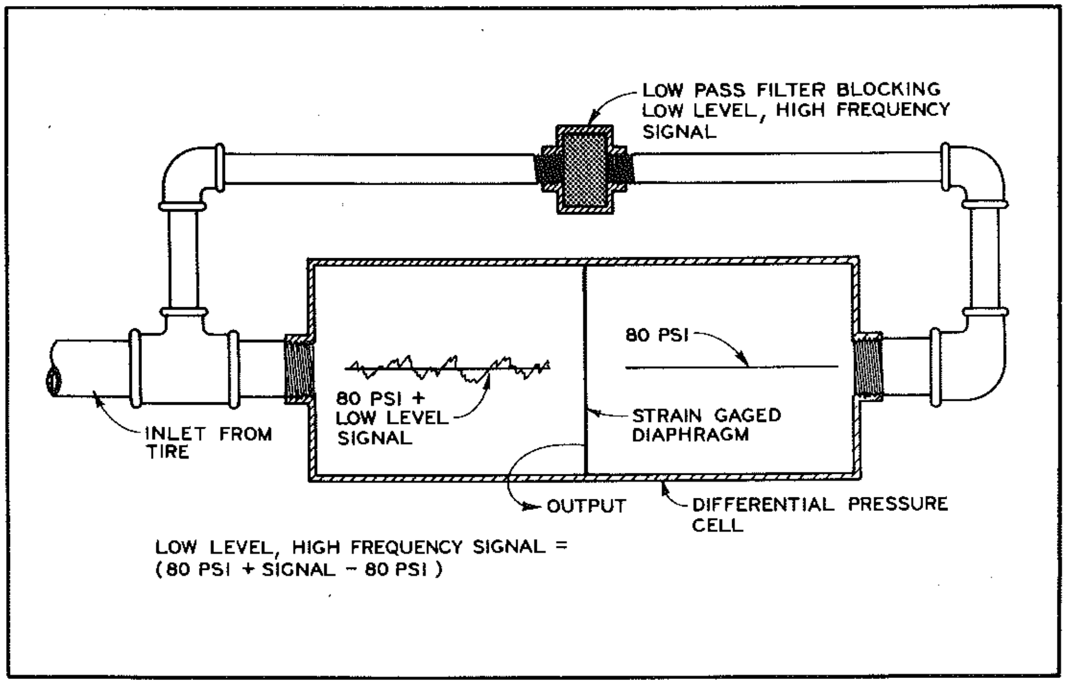


Figure 1. High pass filtration provided by bleed valve and pressure cell combination.

Accordingly, a needle valve was placed in the bypass line and adjusted to yield a bleed time longer than the longest signal period of interest. These bleed times proved to be highly erratic. A cell - needle-valve combination statically adjusted for a given bleed time gave very different dynamic bleed times and also varied with temperature and general road roughness. Various solutions to this problem were tried including different valves and orifices. Finally, a solenoid-operated bypass valve was installed and opened periodically during a run to equalize pressures. The resulting data had segments of baseline drift which were minimized when data were read from the traces.

A second difficulty with the differential pressure cell involved its sensitivity to acceleration. This precluded mounting the cell at the wheel hub and transmitting the signal by electrical slip rings. Instead, it was necessary to employ pressure slip hubs with hoses leading to pressure cells mounted in the truck body. This protected the cells from high level accelerations but led to contamination of the data from accelerations of the connecting hoses. The problem was solved by employing stiff, low mass plastic tubing in place of heavy, flexible rubber lines.

Calibration Procedures

As noted earlier, the instrumented test vehicle axle housing was to serve as a possible method of calibrating the tire. At this time, it was felt that static calibration of the axle housing was appropriate, but that dynamic calibration was preferable for the tire. This conclusion was derived from studies indicating a different response for stationary and rolling tires. Consequently, the axle was calibrated statically by plotting strain against load. Accelerometers were to be added to the axle and this combination used to calibrate the tire dynamically. Subsequent difficulties in obtaining proper accelerometers and analyzing the data led to another dynamic calibration approach. Air pressure data were recorded as the test vehicle rolled over a prototype electronic scale built by the Department (2). Signal traces from the scale and pressure cells would then be compared to provide the dynamic calibration. This process was further enhanced by attaching impact boards to the scale platform to provide an impulse response function and a synchronizing artifact in the two signals.

Analysis of data from this pilot program showed fair correlation between the two signals, but with standard errors of estimate that indicated need for further refinement. Based upon the limited work completed, it appeared possible that further refinements in instrumentation and a possible return to instrumented axles for tire calibration would produce a tire-force transducer system of usable accuracy. This led to the modified research proposal for the work reported in the rest of this paper. Subsequent work at the Laboratory, at General Motors and elsewhere indicated that the path to success was somewhat longer than originally anticipated.

MODIFIED RESEARCH PROGRAM

The Test Frame

Development of an effective force transducer originally was thought to be a relatively minor aspect of the overall dynamic force study. It soon became evident, however, that a major portion of the study would have to be devoted to this search. Although the tire seemed doomed as a transducer, its many advantages prompted a renewed and more detailed study of its behavior. The plan devised called for detailed investigation of an easily handled, auto sized tire. Favorable results for the test tire might be transferable to truck tires. Unfavorable results would settle the tire issue at little overall cost or effort. The experimental procedure was:

1) Mount a simple tire in a suitable frame such that actual force into the tire could be measured under dynamic highway conditions

2) Compare this signal with changes in tire air pressure
3) Work out details of the pressure cell bleed valve and develop calibration techniques.

Accordingly, a test frame similar to a BPR Roughometer was constructed and fitted with a standard ASTM E 17 Test Tire manufactured under close control (Fig. 2). Instrumentation consisted of:

1) A high quality air pressure slip hub to tap off tire pressure for a differential pressure cell (Fig. 3).
2) Strain gages on metal plates supporting the axle (Fig. 4).
3) Accelerometers mounted on the axle bearing blocks to sense acceleration of the wheel and axle mass (Fig. 4).

The differential cell with its associated plumbing was mounted close to the slip hub to minimize false pressure readings from vibrating tubing. Instrumentation for this system is shown in Figure 5. The strain-gaged plates supporting the axle were statically calibrated and the test frame made roadworthy.

The Bleed Valve Problem

Importance of the bleed valve cannot be overestimated for this or any study involving differential air pressure cells. As mentioned earlier these cells have high sensitivity to small changes in pressure but cannot tolerate large pressure differentials. When used in a high ambient pressure situation, such as a truck tire at 90 psi, the cell diaphragm can be ruptured by a change of only 1.7 percent in average pressure since its range is $\pm$ 1.5 psi. The problem reduces to getting the average ambient pressure around behind the diaphragm but preventing the rapid pressure changes representing dynamic force from doing so. As seen earlier, this problem requires a signal filter in the bypass line that passes the "d. c. " or average tire pressure level but blocks the "a. c. " component. The bleed valve was studied in terms of its signal filtration properties.

It was first decided that an orifice valve could be subject to dirt or disturbed settings so a new type valve was constructed of filter paper. Figure 6 shows a 1/4-in. brass fitting that clamps layers of No. 50 Whatman filter paper providing a filtration surface 1/8 in. in diameter. The number of layers can be varied to obtain any desired bleed time. This filter proved very reliable, stable, and immune to obstruction by small particles.

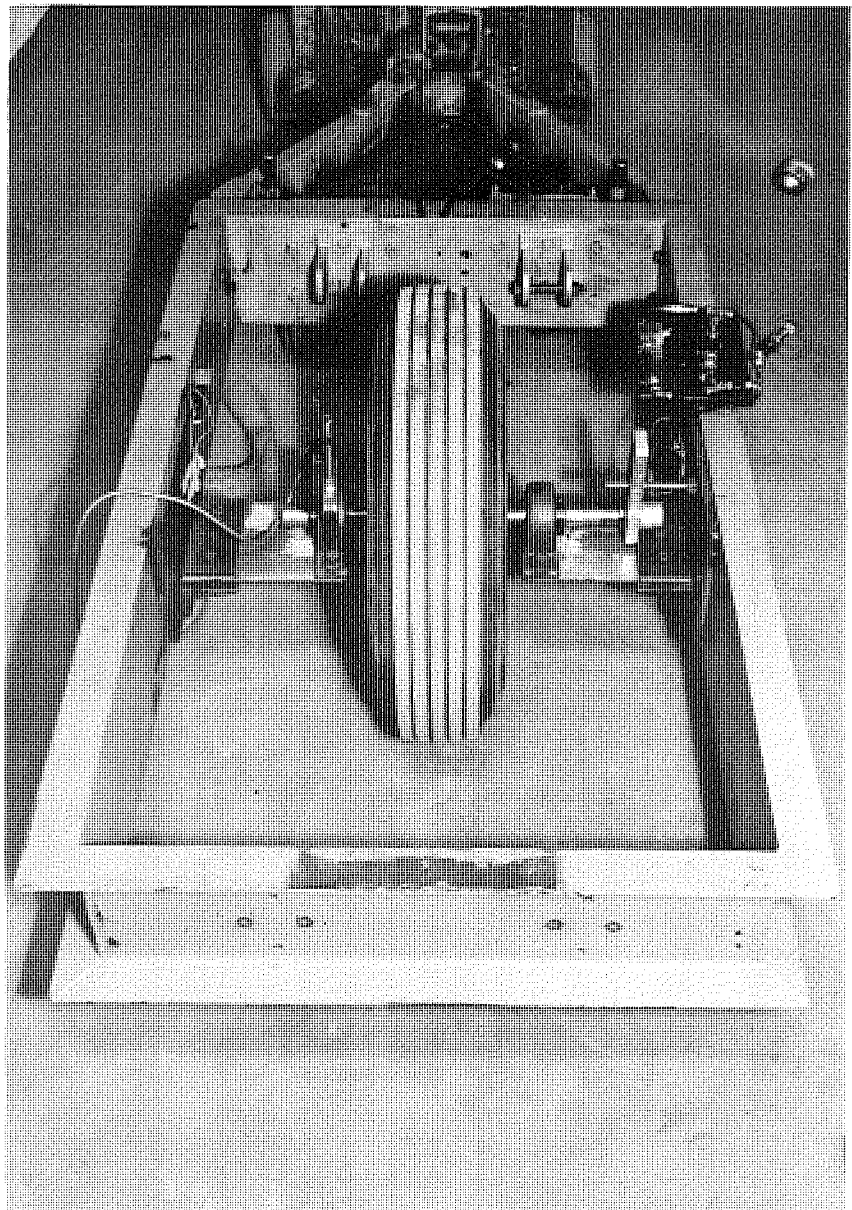
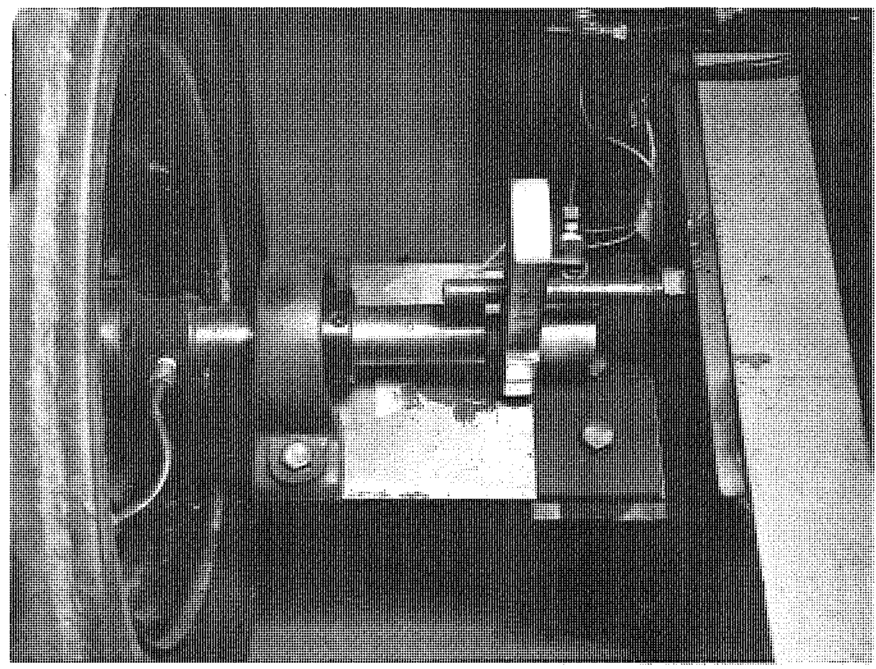


Figure 2. Tire calibration test frame.

Figure 3. Air pressure slip hub assembly.



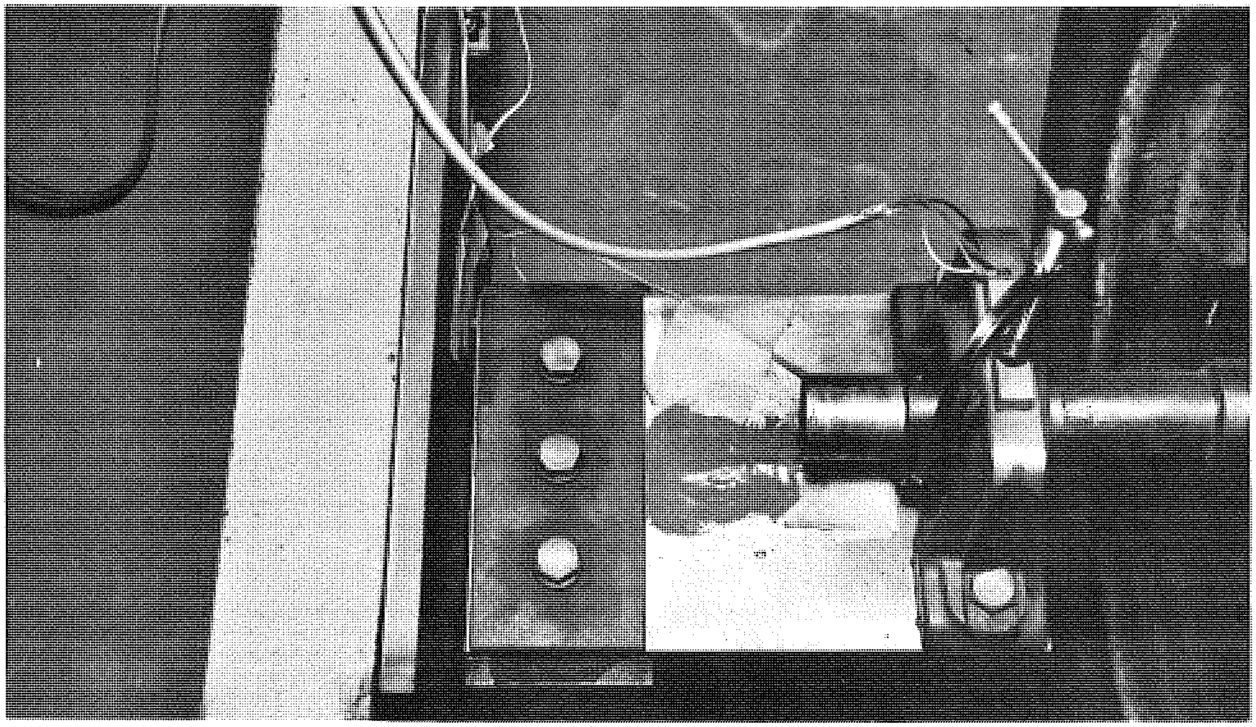


Figure 4. Strain gaged support plate and accelerometer.

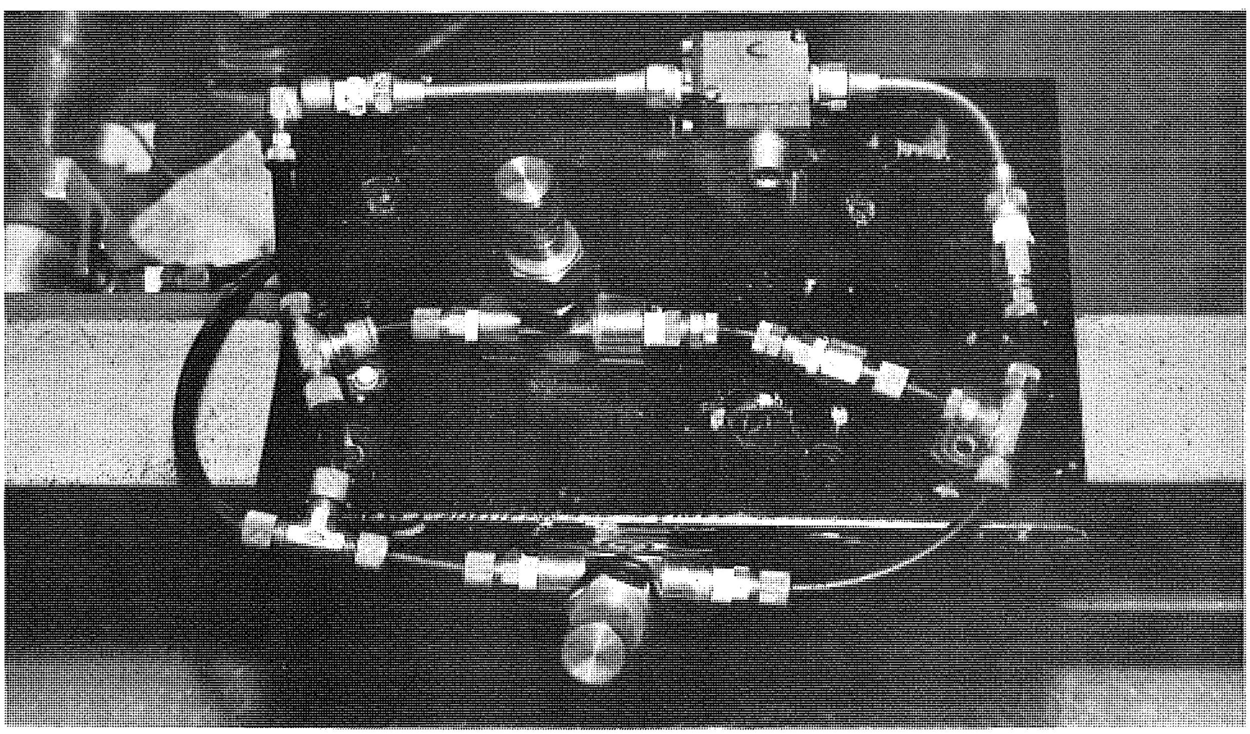


Figure 5. Differential pressure cell, bypass filter and associated valves.

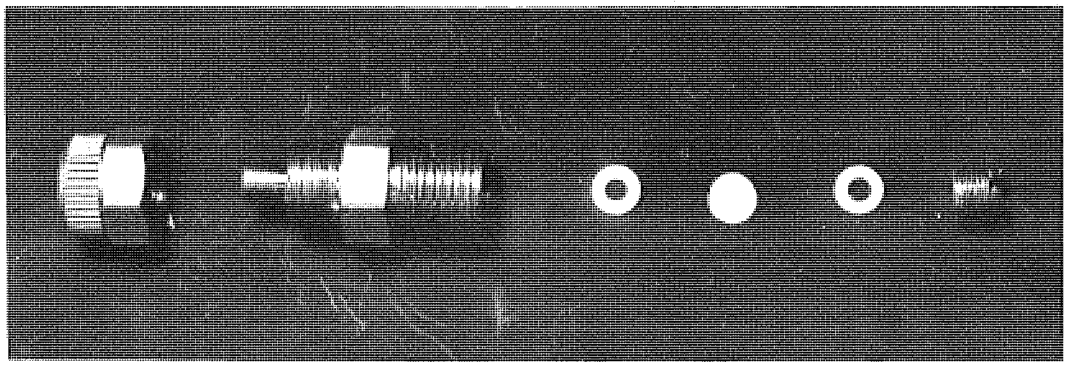


Figure 6. Bypass bleed valve filter shown disassembled.

Next it was decided to obtain a system response function for the pressure cell - bleed valve combination. A step function was put into the system by blowing up a balloon, connecting it to the input and waiting until the system equalized. The balloon was then punctured providing the required step input. It was immediately apparent from the output graph that the filter provided an exponential decay of the form $p = Pe^{-\omega t}$, where p is the pressure at any time, t, and P is the initial pressure. The number of filter paper layers determines the time constant ($1/\omega$). This makes the bleed valve and pressure cell combination a first order, high-pass signal filter with a Bode plot as shown in Figure 7. The rate of attenuation is 6 db per octave below the breakpoint as expected for a first order filter. The breakpoint is given by $\omega = 2\pi f$ where f is frequency in Hz at the desired breakpoint. It was now a simple matter to select the time constant desired and be assured of reliable filtration. Normally, the breakpoint was set very low to remove only the long term, hence low frequency, baseline drifts.

An important property of such valves was discovered during their development. A filter incorporated into the 24 psi ambient pressure environment of a test tire was found to have a bleed time equal to approximately one-half of that established in the laboratory at atmospheric pressure. It was first thought that higher ambient pressure had compressed fibers in the filter paper allowing air to pass through more easily, causing a shorter bleed time. This hypothesis proved incorrect however, since the same phenomenon was observed when a metal orifice was substituted for the filter paper. It was concluded that the effect was probably due to some aspect of the gas laws not explored during this study. The problem was not pursued further since it was a simple matter to add more filter paper until the correct time constant was obtained for a 24 psi environment. It is necessary, therefore, to adjust the bleed valve time constant for the ambient pressure a cell will be working in.

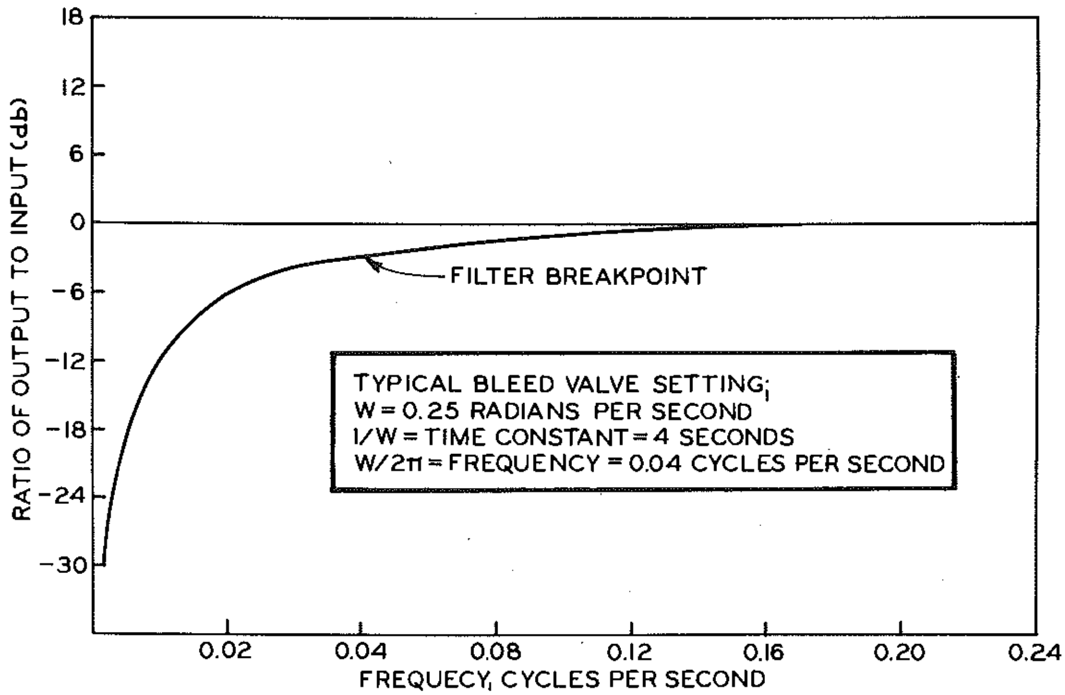


Figure 7. Frequency response function for bleed valve-pressure cell combination (Bode plot).

Tire Pressure Dynamics

A puzzling aspect of early research was the lack of agreement between static and dynamic tire calibrations. At least one reason for this was discovered during study of the test tire. A step load was placed on the test frame while recording output from a pressure cell connected to the tire. The oscillograph read up-scale in step fashion as expected. It then descended asymptotically over a period of about four seconds to a reading some 25 percent below the maximum. This could not have been a system leak since the level did not continue to fall. Subsequent tests, both on the tire and on a pressure test stand, verified that air heating or cooling was occurring despite the small pressure changes. It should be noted that while increased pressure causes the system to lose heat, a decrease in pressure allows the system to take on heat. In either case the recorded pressure would drift back toward the baseline (Fig. 8). The oscillograph drifted back because adiabatic conditions (no heat loss or gain) were not maintained. This would, in general, be the case for static calibration because the delay in placing or removing weights permits heat loss or gain. Under dynamic conditions, adiabatic conditions would prevail because changes in pressure do not hold

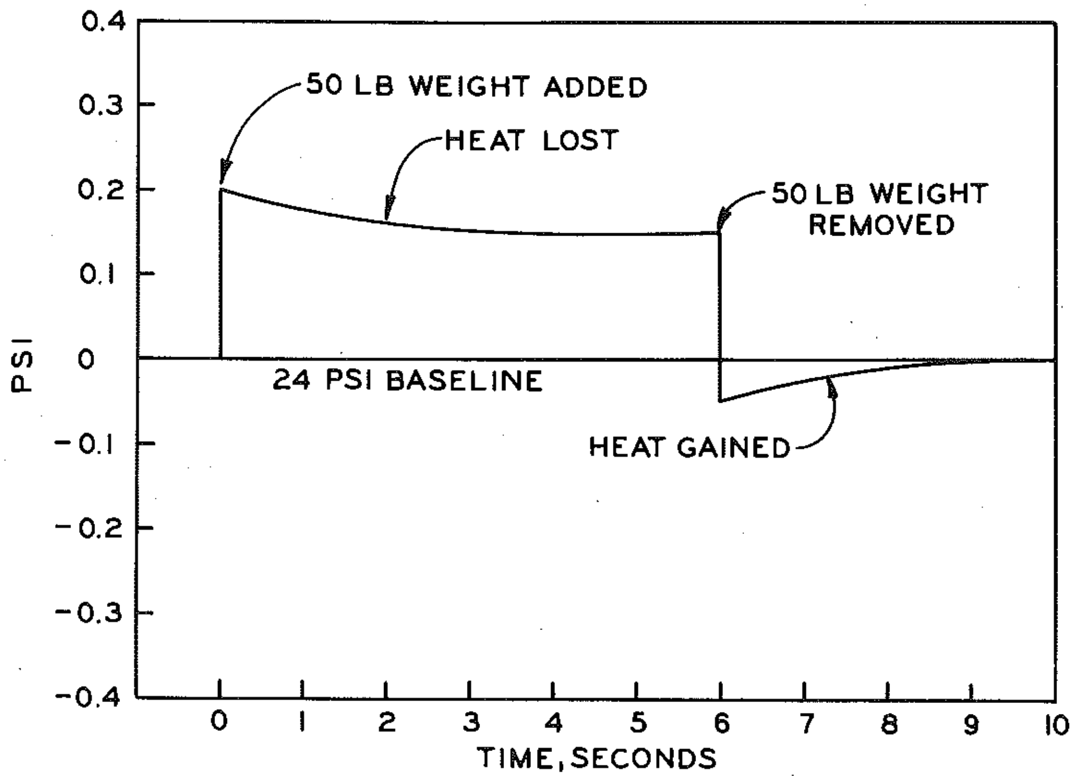


Figure 8. Effect of heat loss and gain on static tire pressure calibration.

long enough for heat loss or gain. Thus, any dynamic tire calibration scheme must be rapid enough to qualify as taking place under adiabatic conditions.

A caution is in order at this point. Depending on characteristics of a particular truck tire or test site environment, it is conceivable that heat loss or gain could be fast enough to reduce low frequency force amplitudes. In view of the 25 percent drop seen for the test tire it might be well to check a new tire or test environment by placing a step load on the truck and noting settling time of the force signal. This would provide the time constant for what is effectively a first order, high-pass filter with limited attenuation. The time constant would then indicate which frequencies are being attenuated so that corrections, if necessary, could be made during data analysis.

In addition to this problem, several other factors may have affected agreement between static and dynamic calibration. Most notable of these is a nonlinear and phase-shifted relationship between pressure change and pavement load (3). Discussion of these problems and possible solutions appear later in this report.

It was also suspected that the frequency response curve for tires is not flat. That is, for a fixed force sinusoidal input, tire pressure peak-to-peak values vary with frequency of the input signal. A frequency response plot for a small truck tire has been obtained as shown in Figure 9 (3). Inspection of the curve reveals an essentially flat response from 0 to 12 cps. At 60 mph this frequency range encompasses profile wavelengths from infinity to 7.3 ft. If force caused by wavelengths shorter than 7.3 ft is desired, weighting should be applied that will exactly compensate for error introduced by the tire. It would be necessary in this case to perform a frequency response plot for each type of tire used. This would be the method of choice for all tire evaluations but it is difficult to find the apparatus needed to perform this analysis on large tires. This would be particularly true if it were found necessary to have the tire rolling. Another method for obtaining a frequency response plot for a rolling tire under dynamic conditions would be a comparison of the tire pressure Power Spectral Density function with that of the true force signal.

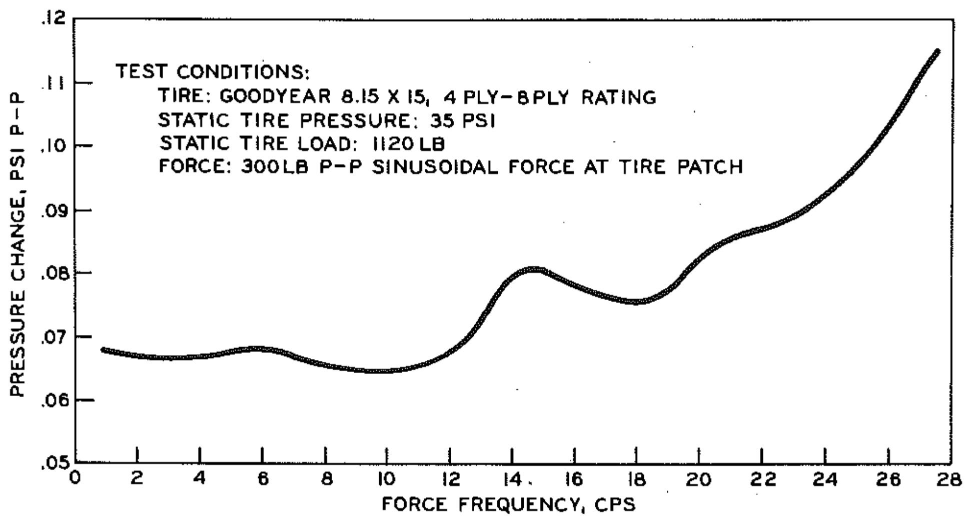


Figure 9. Tire pressure vs force frequency, non-rolling tire.

Calibrating the Test Tire

The test frame tire was calibrated dynamically (under adiabatic conditions) in the laboratory by swiftly loading it through its range and recording both strain gage and pressure cell output. Since the axle-support-strain gage plates were previously calibrated, it was possible to plot load against air pressure output to yield the graph shown as Figure 10. A cubic equation form with missing constant term was fitted to the data by least squares. The fit was so close that a standard error was not calculated. To test the validity of this calibration, a dynamic calibration on the road was next performed.

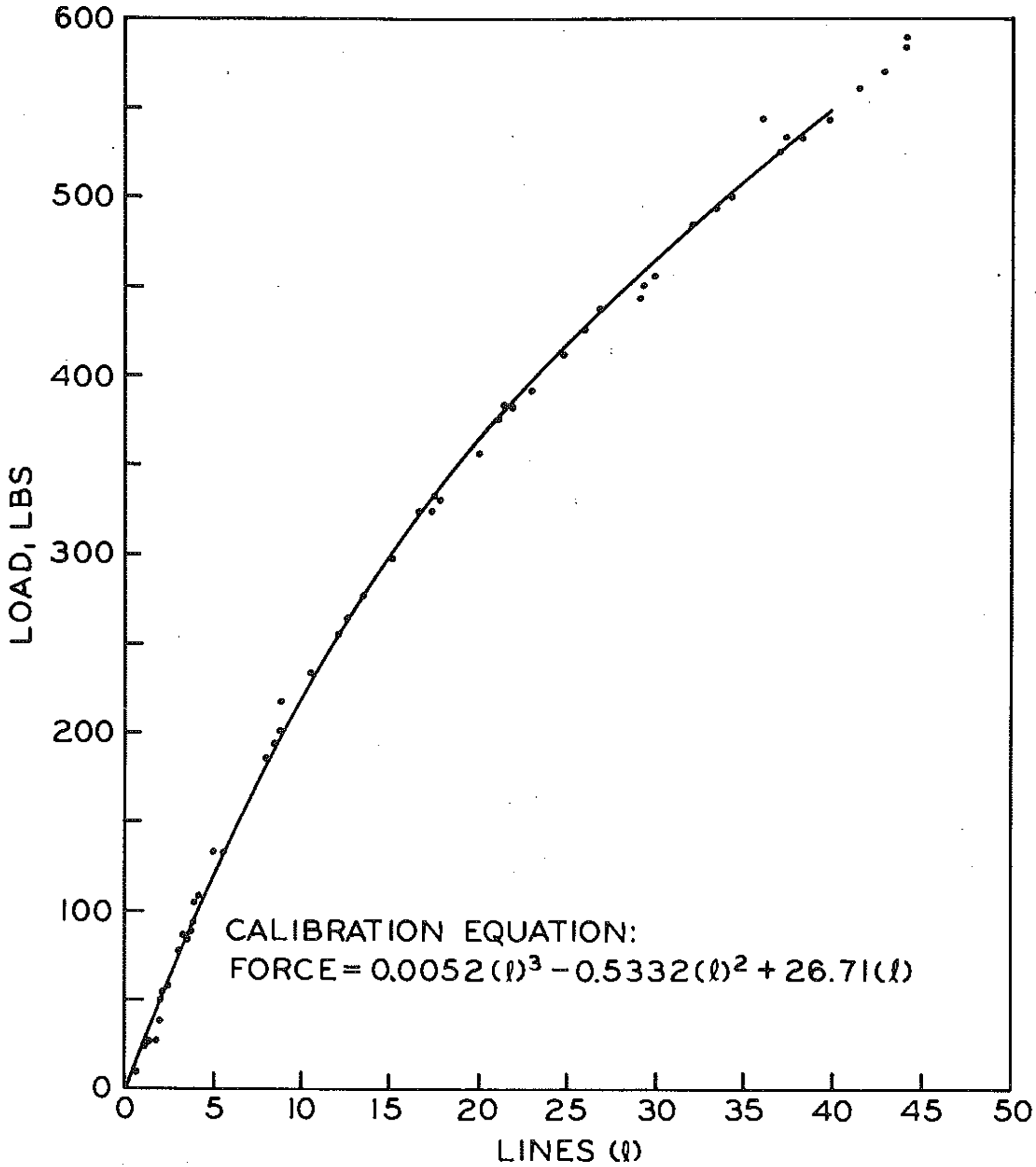


Figure 10. Dynamic calibration of test frame tire.

Dynamic calibration on the road was accomplished by towing the test frame behind an instrument trailer and recording strain, acceleration of the wheel assembly, and tire air pressure. The data were digitized and then pressure was plotted against force from the strain plates alone, and against strain plate force corrected by acceleration times mass of the wheel assembly. Acceleration correction improved the agreement between force and air pressure as expected. A plot of corrected dynamic force against air pressure was in substantial agreement with dynamic calibration obtained in the laboratory.

Calibrating the Truck Tire

Success in calibrating the test tire provided impetus for the next step; calibration of a series of truck tires to be used on various test vehicles. The Department had two vehicles, which together could accept the tire sizes needed for a general truck survey (Figs. 11 and 12). Duplication of the test frame procedure required strain gage and accelerometer instrumentation of each vehicle's rear axle. Figure 13 shows one accelerometer and a strain gage installation on the long-bed trailer. The accelerometers were mounted as close to the wheels as possible to get a realistic acceleration of the outboard mass. This mass is considerable and includes the tire, rim, brake assembly, bearing assembly and a portion of the axle and spring assembly between the accelerometer and wheel. Masses of these components were determined by disassembly and weighing in the laboratory. An important aspect of instrumentation was the use of FM telemetry units mounted on wheel hubs to transmit air pressure data to the instrument bay (Fig. 14). This greatly simplified air pressure instrumentation and virtually eliminated tube-vibration noise by eliminating long air lines. The problem of false pressures induced in the pressure cell by vertical acceleration of the wheel hub was eliminated by using new cells with small diaphragms and by mounting the cells with the diaphragm and wheel planes parallel. A two axle van and a special tractor towed long-bed trailer were so instrumented. Recording equipment was located in the Department's Profilometer truck and towed behind the van for runs with that vehicle (Fig. 15). Instruments were located in a small cabin on the long-bed trailer during that test series (Fig. 16).

The experimental procedure was:

1) Select various test sections on concrete and bituminous pavements of "good," "average," and "poor" roughness. Selection was made on the basis of BPR Roughometer, inches-per-mile roughness.

2) Run the tires to be calibrated at speeds of 25, 50, and 75 feet per-second over a variety of selected test sections and record strain, acceleration, and air pressure on analog magnetic tape.

3) Convert strain and acceleration data to actual force by means of an analog computer program.

4) Digitize the actual force signal emerging from the analog computer and the tire pressure signal to obtain calibration curves in a digital computer.

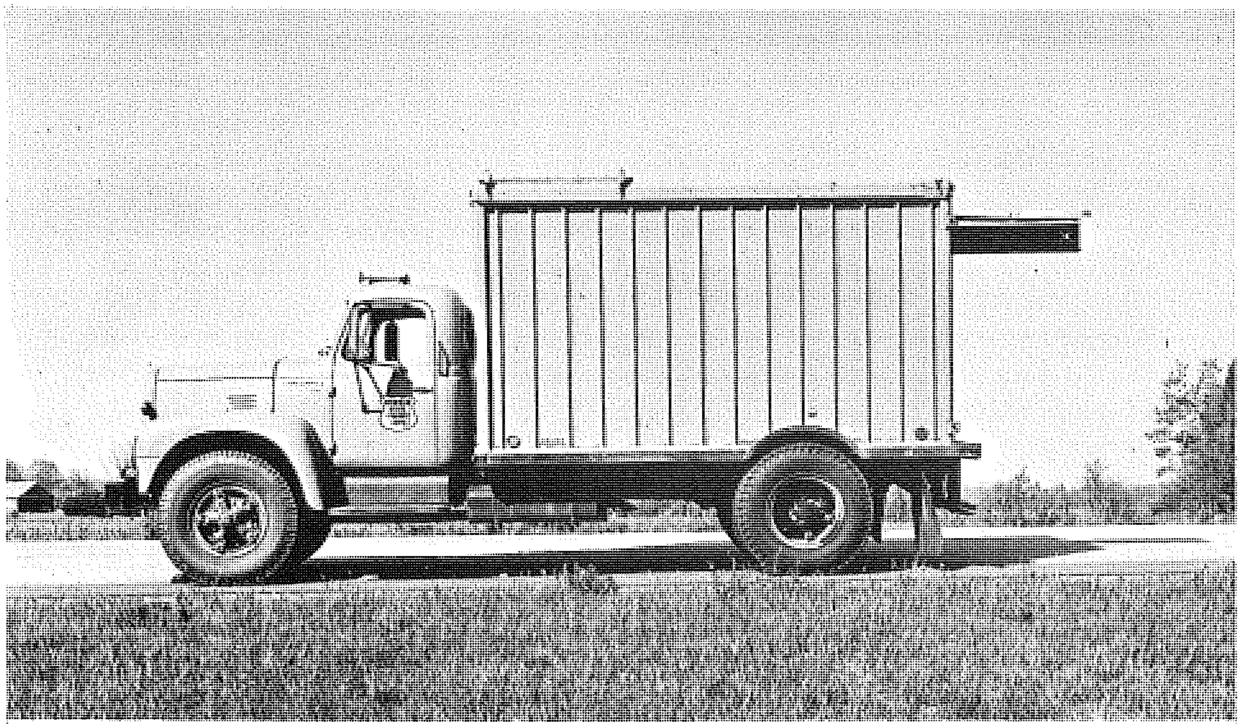


Figure 11. Two-axle test vehicle (2D van).

Figure 12. Long-bed trailer test vehicle.

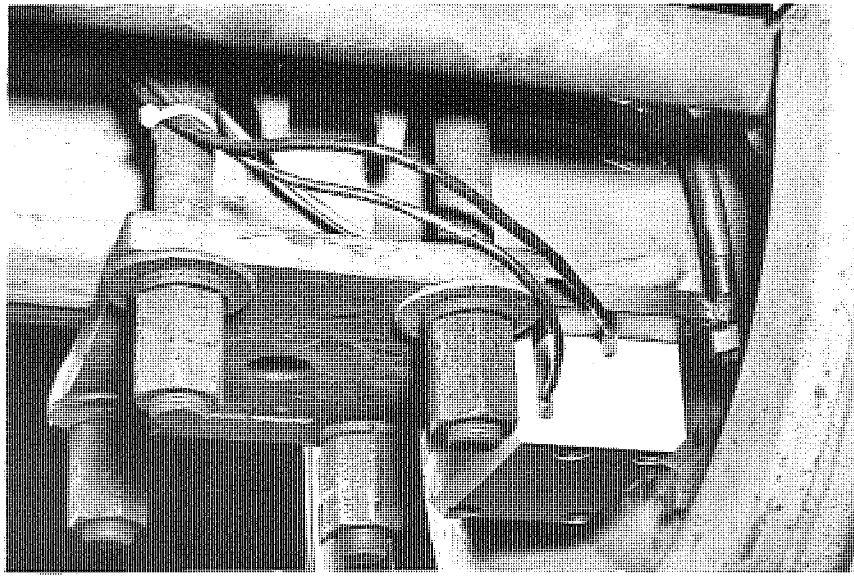


Figure 13. Long-bed trailer axle with accelerometer and one strain gage.

Figure 14. Pressure cell, bleed valve, and telemetry unit (receiving antenna at left).

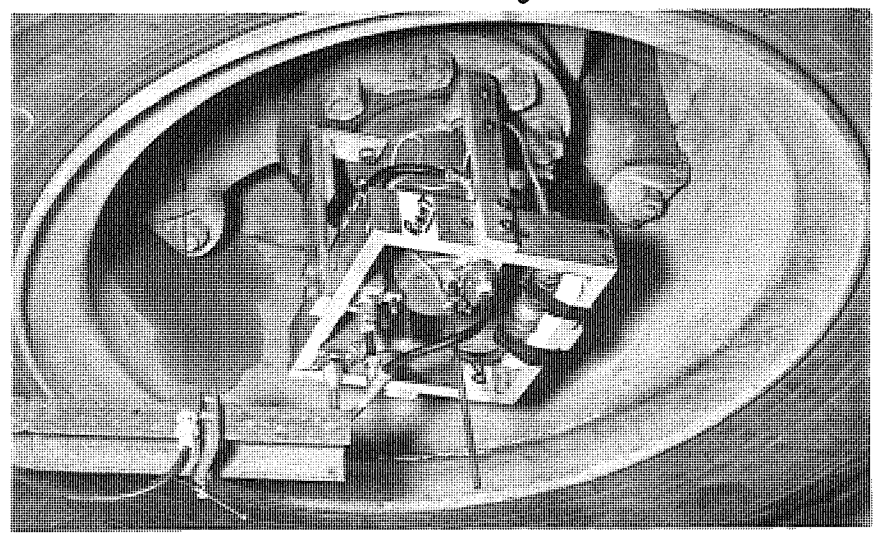
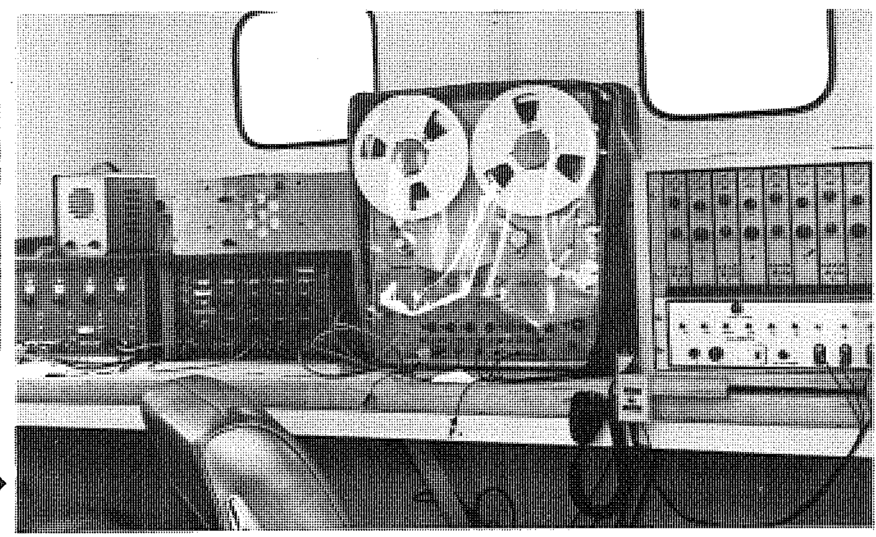


Figure 15. Van test vehicle with towed instrument truck.

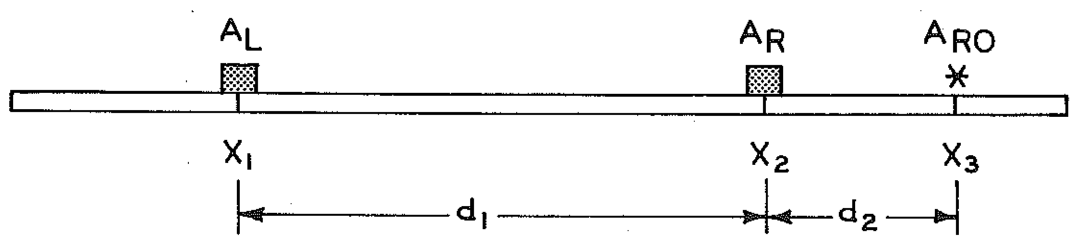
Figure 16. Instruments in cabin on the long-bed trailer.



If calibration curves could be obtained with acceptable standard errors, then two extreme cases of interest arise. 1) The test tires could behave similarly at all speeds on all roads resulting in a single calibration curve. 2) They could be totally dissimilar in all respects resulting in separate calibration curves for each tire at each speed for each road type. Although the actual case probably lies between these extremes, it is of little consequence since even in the worst case a digital computer could select the correct calibration curve. It should be noted that the form of calibration curve is not critical, providing the standard error is acceptable. Thus, the only condition imposed on calibration data is that they have an acceptable standard error of estimate.

Determination of Dynamic Pavement Force

Determination of actual dynamic force from strain and acceleration data was of critical importance. The straingaged axle housings were calibrated by reading force under the wheels with scales while changing load in the truck. Strain output was thus converted to force. The strain gage could not sense forces originating from accelerations of the axle and wheel assemblies located outboard of the gage location. This mass was previously determined, however, during application of the strain gages. Acceleration of the outboard mass times outboard mass would then provide dynamic forces missed by the strain gages. It was not possible to mount accelerometers at the center of gravity for the outboard mass. Therefore, a compromise position was located just inboard of the wheel and a correction equation applied to estimate acceleration at the correct point. Validity of this correction equation rests on the premise that the rear axle housing is essentially a stiff bar under normal accelerations. This assumption was tested by locating accelerometers at the normal positions described above and temporarily at the position where acceleration was desired. One side of the rear axle was then lifted and dropped to provide an acceleration gradient along the axle. Accelerations at all locations were found to be linearly related, thereby supporting the stiff bar hypothesis. Mathematical operations to obtain actual force from strain and acceleration data are derived as follows. Consider the stiff bar shown below, corresponding to the axle housing,



where x_1 is vertical displacement of the left accelerometer A_L; x_2 is vertical displacement of the right accelerometer A_R; and x_3 is vertical displacement at A_{RO}, located at the right, outboard point. Assuming that for any motion of the stiff bar the acceleration gradient along the bar is linear.

$$\frac{\ddot{x}_2 - \ddot{x}_1}{d_1} = \frac{\ddot{x}_3 - \ddot{x}_2}{d_2}$$

where the double dot signifies the second derivative with respect to time (acceleration).

Solving for $\ddot{x}_3$ yields;

$$\ddot{x}_3 = \ddot{x}_2 + (\ddot{x}_2 - \ddot{x}_1)\frac{d_2}{d_1}$$

A similar analysis applies to acceleration for the left side. Because acceleration is in "g" units, $\ddot{x}_3$ can be multiplied by the outboard weight to get force.

Acceleration and strain gage force recorded on magnetic tape were input to an analog computer circuit that performed the above operations on acceleration data and combined it with strain data to yield actual force from right and left sides (Fig. 17). The circuit is essentially self explanatory and uses amplifiers in summing mode only. The lead marked "common mode" and connected to all input amplifiers, cancels tape noise common to all channels by inverting the polarity of noise from an unused channel and adding it to each signal. Accuracy of the forces derived in this manner was checked by runs across the Department's electronic scale installation and was found to be sufficient. In addition, General Motors experience with an identical system on one of their trucks indicated close agreement with their instrumented wheel dynamic force transducer (2). There are, however, several deficiencies in this system which limited accuracy.

Strain gage output was low, because of the stiffness of the axle housing, resulting in a low signal-to-noise ratio. There may have been errors in determining the effective outboard mass or in locating its exact center of gravity. In addition, any departure from the assumption of complete stiffness in the axle housing could generate error accelerations. Despite these problems there were no viable alternatives to measure the actual force at this time and accuracy was considered sufficient to investigate the tire as a force transducer.

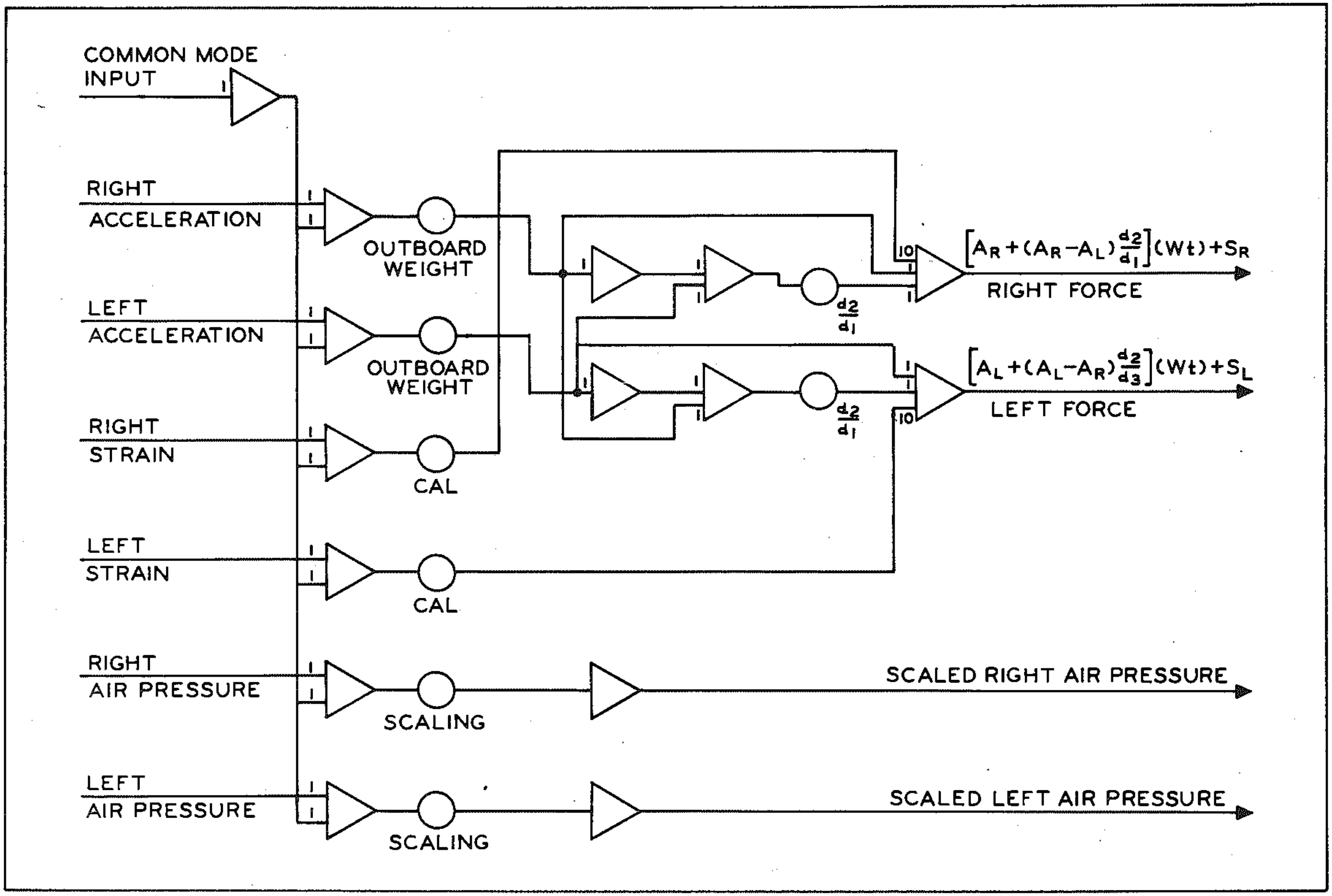


Figure 17. Analog computer force computation circuit.

Phasing Problems

Calibration runs were made with the two test vehicles at speeds of 25, 50, and 75 feet per second on concrete and bituminous pavements of "good," "average," and "poor" roughness. Two pairs of tires were to be calibrated on the van and another two pairs on the long-bed trailer. At this time computer programs were written to produce calibration curves from the field data. Field data were first passed through the analog computer, force computing circuits and then digitized. At this time it was evident that although the air pressure and force signals looked identical in shape and amplitude, there was a varying phase shift between them. Moreover, the shift was found to be of two types.

1) There is a slowly varying random difference in the force and air baseline distances per unit time. It's as if force and air were recorded on different tape recorders with randomly varying tape speeds (Fig. 18). Since both were recorded on the same tape deck simultaneously, there must be another cause.

2) There is a slowly varying random translational shift between the force and air signals. Translational phase shift occurs when either signal is moved along the time baseline with respect to the other (Fig. 19). This could occur if changes in the system during a run caused a varying delay of one or both signals.

These phase anomalies seriously disrupt the calibration process because signals must be read simultaneously at in-phase points to develop the calibration curves. It must be emphasized that these shifts, though small, are large enough to increase standard error of the calibration curves. Their elimination would reduce the standard errors from barely acceptable to completely acceptable. A typical case would be one standard error equals 450 lb for no phase correction, to 50 lb with correction of both phase errors.

At the time this is written the first type or baseline difference phase shift has been greatly reduced by means of a complex computer program. A second program to reduce the translational phase shift is in the development stage. The first program has resulted in substantial reduction of standard errors from 450 to 150 lb on the average. It is based on a scheme of making small changes in the baseline for small segments of the signal and then testing the fit of force and air data by cross correlation. When a maximum cross correlation is obtained, the data for that segment are stored and the program moves to the next segment. The process converges very

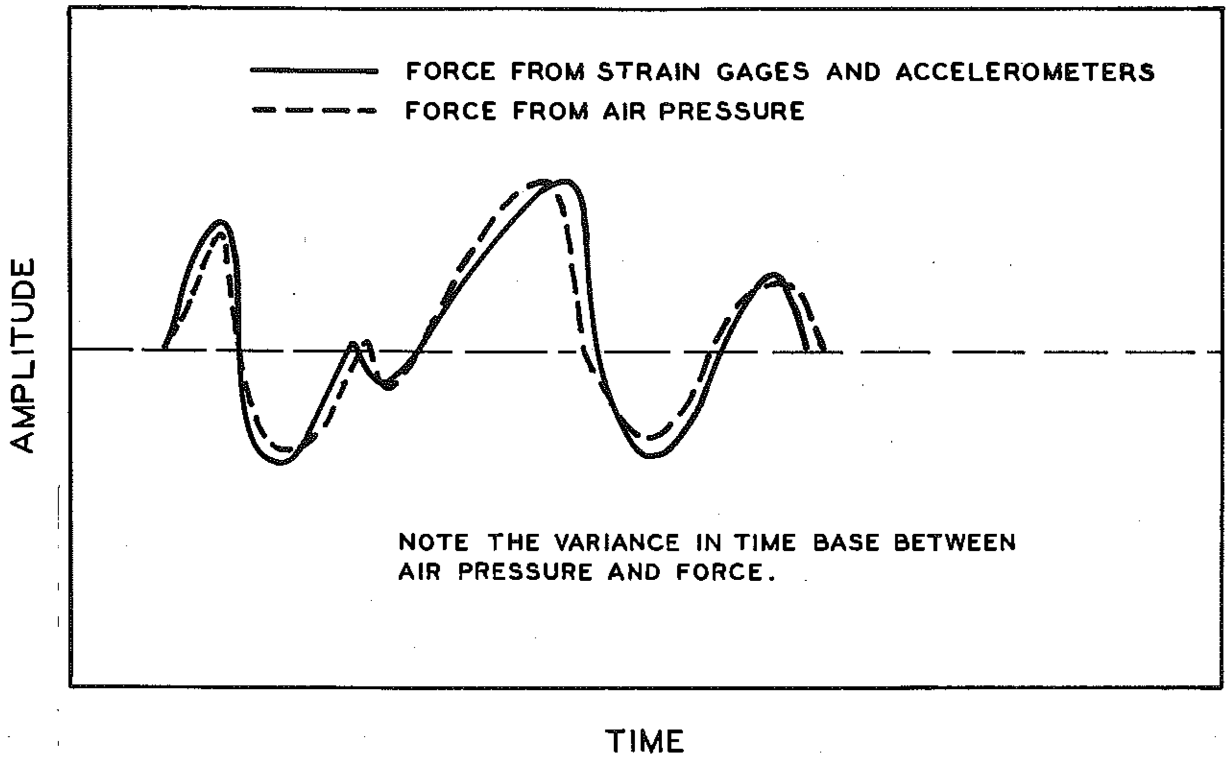


Figure 18. Baseline phase shift.

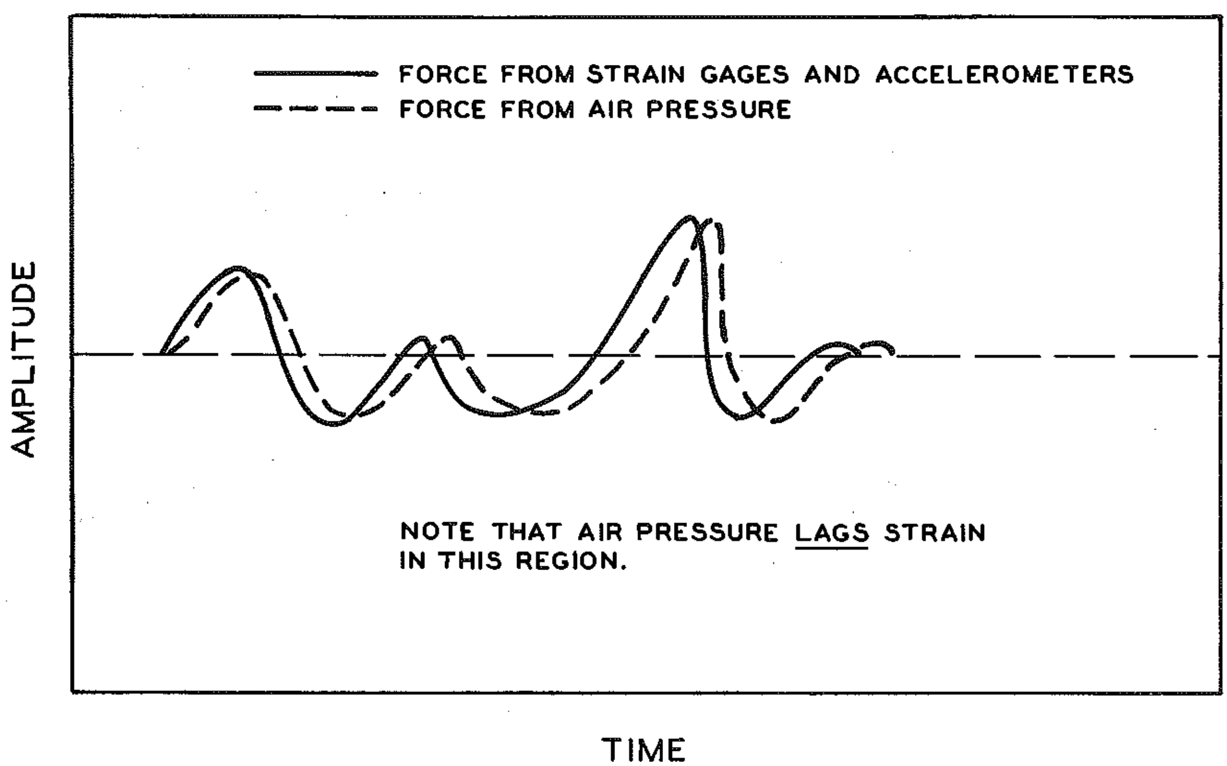


Figure 19. Translational phase shift.

quickly to minimal baseline error. The second program, still in development, first removes any translational phase shift for the entire sample period by means of cross correlation. It then makes small changes in translational phase shift for small segments of data and tests the fit by cross correlation. When maximum correlation is obtained it stores data for that segment and moves on to the next. Preliminary results indicated that this program would substantially reduce the remaining phase error between signals.

Calibration Results

Some calibration computations were performed by the existing program without assistance from the translational phase correction routine. The processing scheme for one run is as follows:

1) Strain, acceleration and air pressure data are fed from the tape deck to the analog computer force computation circuit.
2) Forty-five seconds of data were automatically digitized as they emerged from the analog computer providing two samples of digital force and air pressure data for each cycle of the highest frequency present.
3) The digital magnetic tape was then processed by the program described above as follows:

A) Overall translational phase shift, if any, is removed by cross correlation.
B) The baseline correction routine is called to correct the baseline differences.
C) The force and air data are then in partial phase and points from each form the data for an x, y plot to which various equation forms are fit by least squares.
D) The equation form resulting in the least standard error is used to calibrate the air pressure data.
E) The force and calibrated air pressure data are then plotted on the same axis to show accuracy of fit.

Typical results of this operation for a series of the two axle truck calibration runs are given in Table 1. The equation type fit by the computer was linear. A plot for Run 1 is shown in Figure 20. The plot shows force from strain and acceleration plotted along with force derived from air pressure by the method described above. They are plotted on the same axis but air-derived force can be located by noting that it is usually the inner trace and does not rise as high as strain-acceleration force. Although the agreement is quite good, careful examination of the plot will reveal the slight translational phase shifts that still remain. The air pressure force

TABLE 1
LINEAR CORRELATIONS BETWEEN ACTUAL FORCE AND FORCE DERIVED FROM AIR PRESSURE

Run	One Standard Error, lb		Correlation Coefficient	
	Left Side	Right Side	Left Side	Right Side
1	92	82	0.965	0.971
2	108	120	0.953	0.950
3	126	124	0.935	0.941
4	88	80	0.885	0.946
5	90	103	0.955	0.946
6	100	104	0.891	0.906
7	125	150	0.956	0.934
8	162	167	0.924	0.916
9	134	131	0.811	0.894
10	90	84	0.919	0.942
11	148	168	0.910	0.914
12	156	161	0.919	0.909
13	86	111	0.954	0.941
14	156	160	0.594	0.635
15	137	138	0.948	0.949
16	136	164	0.939	0.905
17	165	125	0.850	0.911
18	175	188	0.944	0.935
19	138	161	0.912	0.892
20	156	183	0.918	0.885
21	149	182	0.930	0.908
22	101	131	0.944	0.909
23	154	165	0.868	0.874
24	193	195	0.870	0.884
25	131	154	0.713	0.753

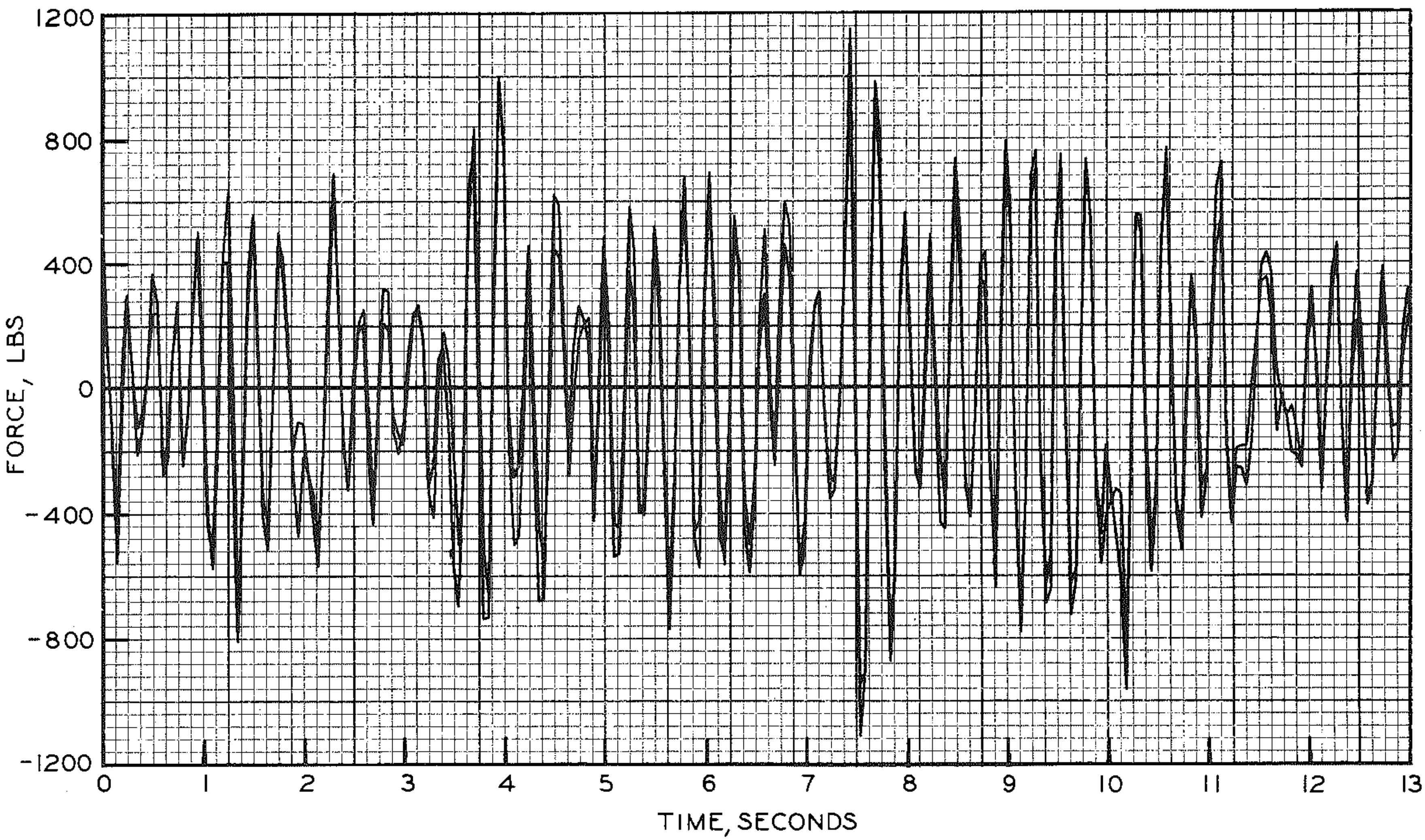
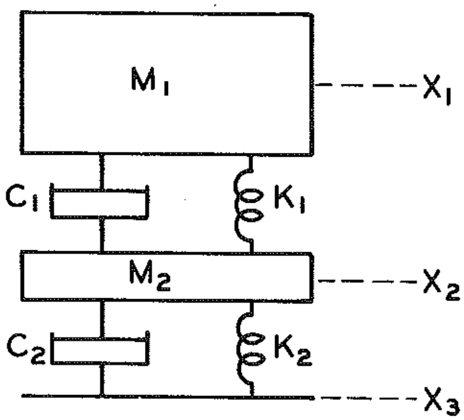


Figure 20. Actual force from strain and acceleration plotted congruently with force derived from tire air pressure. Baseline drift correction procedures were used.

would have fit the actual force somewhat better on the peaks if a nonlinear equation had been fit. Overall, the fit would be significantly improved if the translational phase shift were reduced.

An Analog Computer Model

While building the test frame, it was decided that an analog computer model of the frame could provide additional insight into the calibration problem. All parameters necessary to synthesize such a model were measured during construction. This included all spring constants, masses, and damping coefficients. The model proposed was a two-degree of freedom, quarter-car simulation as shown.



where M_1 = Mass of frame

M_2 = Mass of wheel and axle

K_1 = Support spring constant

K_2 = Tire spring constant (static)

C_1 = Frame damping constant

C_2 = Tire damping constant

X_1 = Position of the frame

X_2 = Position of the axle

X_3 = The road profile.

Profiles of test sections used for the actual frame were recorded by the Department's Rapid Travel Profilometer. These were fed into the model through a first order high-pass filter which simulated the tire enveloping function (3). Comparison of force traces from the frame with those from the model did not compare well. It is believed that simplifying assumptions for the model and non-linearities in the test frame combined to limit the degree of agreement. Nevertheless, it is felt that a comprehensive model could provide insight into tire behavior.

SUMMARY

Results to date show a high probability that truck tires may be used as dynamic force transducers with standard errors of estimate less than 100 lb. Separate calibration curves and frequency weightings may be needed for each tire or class of tires. Either case, however, can be handled by computer processes so there would be no great difficulty if each tire did require a separate calibration. The computer can also solve the phase-shift problem that occurs during tire calibration procedures.

The serious problem of high amplitude, low frequency pressure drifts has been solved by the use of an improved type of bleed valve. This valve permits use of highly sensitive differential pressure cells without fear of cell damage or data contamination. Bleed valve time constants can be precisely, and permanently set. Six decibels per octave attenuation of low frequencies is provided without distorting higher frequencies of interest.

Frequency response problems of rolling truck tires appear to be minimal (3). If substantial frequency response problems were encountered, however, they could be easily compensated out by proper frequency weighting. This could be accomplished by analog computer techniques during the data analysis phase.

CONCLUSIONS

The acquisition of knowledge is a continuous, open-ended endeavor. Consequently, this study, as with most such studies, can be appropriately concluded with the researchers views on the need or direction for further investigation relative to the subject area. In addition to the possibilities for future vehicle dynamic load work, however, there are two specific conclusions derivable from the study's results.

1. The use of vehicle tire pressure variation as a measure of the dynamic forces input to highway pavements has been shown to be a technically feasible and reasonable cost technique.

2. The tire pressure technique is the best currently available method for use by any researcher or agency considering, or involved in, large scale studies of the pavement forces input by in-motion, highway vehicles.

As pointed out in the report, this study spanned a number of years and the field and laboratory work were both completed some time ago. That time lapse plus the experiences gained during the study form the basis for certain secondary conclusions, or recommendations, for future work on the problem. These are:

3. Of the many techniques available for random signal analysis, the power spectral density function (PSD) offers the most promise for accurate insight into the vehicle - road interaction phenomenon (4, 5).

4. All aspects of the work accomplished in this study could be more efficiently and economically completed today because of the significant advances in instrumentation, telemetry and computational devices. These advances, including improved sensors, signal conditioning equipment and mini-computers, make it feasible to consider studies wherein all phases of signal sensing, manipulation and computation are performed on-line, in the field.

5. The technique now available for relating pavement load to vehicle tire pressure opens up the possibility of valuable peripheral studies related to the dynamic vehicle load. Such possibilities include:

a. Vehicle transfer functions will now be obtainable by combining the vehicles force PSD with the road profile PSD.

b. The effects of vehicle variables such as loading, speed and suspension system variations are all readily quantifiable by varying these factors in subsequent runs over the same test sections, and then examining the resulting force PSDs.

c. The rational design of electronic scales for weighing in-motion vehicles has long been hampered by a lack of information on the load spectrums of highway trucks. Obtaining such spectrums is now feasible by the tire pressure method; and once accomplished, weighing systems can be designed by noting the highest frequency at which substantial forces occur, translating this frequency to distance from the scale design speed, and then installing two peak value scale platforms per this unit distance. The number of scale platforms needed to achieve any desired system accuracy can also be easily determined.

d. It is now conceivable, although it would be a very large-scale, long term undertaking, that a study program could determine the frequencies and power levels primarily responsible for structural damage to highways.

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