MEASUREMENT OF SHEAR FORCES DEVELOPED BETWEEN TIRE AND PAVEMENT

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Mobile apparatuses have been constructed and employed to evaluate the shear forces produced by pneumatic tires on actual paved surfaces. These devices have permitted extensive examination of tires designed for service on passenger cars and on light and heavy trucks. Considerations of system design and mobile test methodology are discussed as they constitute a special interest within tire test technology. The specific design characteristics and capabilities of mobile traction test machines developed at the Highway Safety Research Institute are discussed. Example data are presented illustrating the characteristic measurements for which mobile techniques are most suitable.

This paper addresses the state of technology which has developed to permit the experimental determination of the force and moment generation properties of pneumatic tires on actual paved surfaces. Categorically, the experiments involve the use of mobile machines which impose a set of controlled operating conditions on a tire specimen while the entire machine travels across a specimen pavement. Such machinery and experiments share a number of features and techniques with laboratory test approaches using fixed machines and (usually) artificial "roadways." The mobile machine and associated test methodology, however, generally requires a number of specialized design characteristics which will be discussed here. Further, it is characteristic that mobile test techniques are especially applied to the examination of high slip phenomena--that is, as pertain to the severe cornering and braking maneuvers of vehicles. As is well known, the shear force production of tires at high values of angular and longitudinal slip is determined by frictional mechanisms which depend upon the surface texture as well as the velocity condition under which the tire operates. Clearly, then, the mobile methodologies employed in tire shear force measurement are primarily justified by, firstly, the need for pavement authenticity and, secondly, the need for highway-type test speeds—although certain laboratory apparatuses can meet the speed requirement.

Mobile test techniques provide data which are useful to the technical communities representing tire and/or highway-related interests. Regarding the latter, of course, skid-trailer-type devices and methods have been standardized by the American Society for Testing and Materials (ASTM) principally as a means to assess the acceptability of the extant friction potential of roadways within a given highway system. This paper, however, is more generally addressed to the state of the mobile traction measurement art as it has been pursued by those for whom the tire constitutes the independent variable and for whom the road section represents merely a selected test condition.

The use of machinery specially engineered for this purpose appears to date back to the 1930's, although the era of comprehensive measurements of tire shear force and moment behavior would seem to have been initiated with the development of a six-component device at the Cornell Aeronautical Laboratory in 1954 (1). This device permitted operation of passenger car tires under the full complement of angular and longitudinal slip and camber conditions, over a range of tire loads and speeds. Major contributions to the tire mechanics literature were later provided from measurements taken on mobile machines developed in the U.S. and in Europe in the sixties (2, 3, 4). Publication of data describing truck tire shear forces as measured at highway speeds on mobile apparatuses did not appear until 1974 and 1975, covering longitudinal properties (5, 6, 7, 8) and 1976, covering lateral properties (9).

Design Features of Mobile Tire Test Machines

All mobile tire traction dynamometers incorporate a foundation vehicle whose function is to tow, direct, and, at least partially, support the tire-locating apparatus as it travels. Mobile machines have been constructed in the form of (a) unit vehicles, on which the tire support assembly is attached to the foundation vehicle frame (e.g., 1, 2, 4, 10) or (b) tow vehicle and trailer, with the tire support assembly located on the trailer (e.g., 5, 6, 11, 12). Regardless of the specific arrangement of vehicle units and tire support assemblies, the key design criterion peculiar to the mobile environment would appear to be the need to tolerate roughness in the test pavement without suffering excessive variations in the vertical load condition. This primary design interest is distinct

from that applied to laboratory machines, of course, since laboratory test apparatuses employ very smooth, rigidly located roadways as well as rigidly located wheel supports. The tire which is tested on a mobile apparatus experiences load changes which derive, in part, from road profile fluctuations whose frequency content includes significant components in the vicinity of, and above, the "wheel hop" natural frequency of the test wheel assembly. Accordingly, a fundamental design objective is to minimize the mass directly supported on the tire spring thus maximizing the natural frequency of the wheel hop system. Correspondingly, the transmission of vibrations down through the foundation vehicle must be minimized either by means of a soft, perhaps pneumatic, spring-type loading system, or a broad bandwidth electrohydraulic servo load control system and/or a specially-softened suspension system on the foundation vehicle itself to minimize, altogether, the ride vibrations of the foundation vehicle.

A second major design consideration which places peculiar demands upon the mobile-type tire test apparatus is the need to provide for high values of slip and to maintain the various other condition variables while reacting the large levels of shear force developed by the test tire. Since all longitudinal components of shear force require an equal and opposite level of drive thrust from the foundation vehicle if velocity is to be held constant, mobile tire test machines commonly employ irregularly large engines. (Another argument for the large engine derives from the need to accelerate the overall machine up to desired test speeds—even on test facilities affording limited space for "run-up." The primary design variable, however, which serves to minimize the velocity change accruing during a longitudinal traction test is simply the mass of the total vehicle system.)

To react lateral components of shear force generated by the test tire, one of two approaches are taken. If the tire is of passenger tire size, it is possible to provide adequate levels of side force reaction capability by employing a heavy truck as the foundation vehicle. If sufficiently loaded, such a vehicle will accrue negligible levels of body sideslip angle as a result of test tire side force since the cornering stiffness of installed vehicle tires provides a very high-rate spring analogous to the rigidity afforded by the structural character of laboratory apparatuses.

The second approach toward reaction of lateral forces involves the use of two counter-slipping tires whose reaction forces applied lateral to the foundation vehicle are colinear, opposite in direction, and nominally equal in value. While a few such arrangements have been incorporated into machines for testing passenger tires (13, 20), certain practicalities have resulted in the "opposing-pair" configuration being the only approach adopted in machines built to test heavy truck tires (9, 14, 15).

A third aspect which is emphasized in the design of mobile tire traction dynamometers relates to the desire that independently-suspended test wheels incorporate suspension mechanisms which kinematically decouple reaction forces and moments from one another. While kinematic decoupling is a desirable feature in any linkage-supported tire test system, be it for the laboratory or for the mobile application, the need for attenuating tire load fluctuations often encourages the use of a simple linkage suspension system which renders decoupling a significant challenge. Typically, a compromise is struck in the minimization of unsprung mass so that decoupling is achieved.

Additional burdens associated with these apparatuses include the need for incorporating a full complement of mobile support services into the foundation vehicle. Typically, the test system which incorporates servo mechanisms in the wheel-locating functions employs an engine-driven electrical generator, a hydraulic power supply, a compressed air system, an on-board water tank, pump, flow control and nozzle system, and an electronic data acquisition and test control station. Features are often provided for easily changing test tire specimens, for performing quick reference calibrations, for protection of the instrumented wheel suspension in the event of a blowout, and for the convenient recovery of a highway-legal configuration for transport.

Considerations of Mobile Test Methodology

The typical mobile tire traction test involves a condition of constant velocity, constant tire load, and homogeneous pavement condition. The constant velocity condition imposes certain constraints on the configuration of an acceptable test facility; i.e., there must be space provided for attaining the needed speed and there must be multiple hundreds of feet of test-quality pavement to permit a 2- to, perhaps, 10-second slip sequence at highway-type speeds. In the author's experience, oval-type facilities render the mobile test most efficient since speed can be maintained and successive passes over the target pavement can be conducted with a minimum "cycle time." Of course, the overall length of an oval track will determine the cycle time with increased-length tracks providing reduced testing efficiency. Regarding wet testing, crowned pavement lanes are less desirable than planar surfaces which are constructed with a uniformly small side slope (typically, 0.5 to 1.5%). Crowned pavement lanes are objectionable inasmuch as they afford varying water depths across the lateral dimension of the (pre-wetted) lane—thereby providing a source of randomness in connection with the run-to-run variation in lateral position of the mobile apparatus.

The wet surface condition is generally achieved either through a ground-fixed, constant flow watering system, or by means of a test vehicle-borne delivery system whose flow rate is adjusted proportionately to vehicle speed. The two watering methods differ insofar as the ground-fixed system serves to "fill" the pavement texture and further to establish a desired water depth above the asperities while the on-board system is more of a constant volume approach, thereby establishing a somewhat unpredictable water depth above the asperities. By way of explanation, the on-board delivery system with constant flow rate provides a fixed volume of water per foot of longitudinal travel, such that the volume capacity of the pavement texture determines the net depth accrued above the asperities. The on-board method, then, provides advantages in consistency from run-to-run, but suffers in terms of the non-universality of its "net" water depth condition.

A major feature of any mobile traction methodology concerns the manner by which the slip history is induced. Particularly, there is a need to attain a slip history which divorces the dynamic components of shear force generation from the essentially static components. With regard to

the measurement of braking traction, a distinct compromise exists between economics and the attainment of a fully controllable longitudinal slip condition. The simplest and cheapest mechanism for inducing a wheel torque is the friction brake, although such devices render an unstable wheel spin condition when the tire is operated beyond its traction peak. Thus the friction-braked test wheel experiences an uncontrolled slip condition in which a severe dynamic component of longitudinal slip accompanies the nominal static levels of interest. Since a limited body of data has been collected suggesting sensitivities of longitudinal traction behavior to slip rate (16), the matter of widely varying slip transients does, perhaps, tend to degrade the experimental precision of friction-braked mobile traction dynamometers. As a minimum constraint on slip transient, such machines are generally operated with a controlled onset rate of brake torque so that at least the transition through the low slip and the critical peak-traction conditions are rendered somewhat more consistent.

Certain other machines have been constructed to provide a powerful wheel-spin servo mechanism, thereby affording the ability to control the slip transient (10). Such apparatuses, while permitting close examination of slip rate sensitivities, otherwise provide for a more consistent experimental routine.

As has been well known for over 40 years, the pneumatic tire exhibits a first-order sensitivity to rate of change of lateral slip in the generation of side forces. Thus it is absolutely mandatory that any lateral traction dynamometer provide a means of controlling slip angle, α, to the point of excluding dynamic slip angle influences on "static" lateral force, F_y, measurements. This is accomplished either by employing a manually-adjusted slip angle condition (thus leaving α constant throughout the test) or by incorporating a servo control of the slip angle motion and using "staircase" command histories of slip angle during the test sequence. The staircase-type waveform permits discrete characterization of the static F_y/α relationship over a large number of α values in a minimum time.

The time over which the tire specimen endures an elevated slip condition has been found to be a prime concern in mobile test methodologies. Regarding passenger car tires, it has been observed that the tread wear deriving peculiarly from extended operation at high slip can cause profound changes (as much as 35%) in peak lateral traction performance (17) and smaller, but still significant, changes (as much as 10%) in peak longitudinal traction performance (18). Regarding heavy commercial vehicle tires, data has been obtained revealing, again, a large peak side force sensitivity to test-induced tread wear (as much as 20%) but no evidence is known to exist that the longitudinal traction performance of heavy tires is significantly sensitive to test-induced wear (18). It should be pointed out that the dimensions of tread rubber removal required to produce the performance alterations cited is characteristically small relative to the nominal "depth" of the as-new tread. In the case of traction modifications induced by lateral slip, the associated wear is concentrated at outer rib and shoulder, often leaving interior rib positions virtually untouched.

As a consequence of these sensitivities to test-induced tread wear, there is a need for minimizing the total slip-work experience to which a single tire specimen is exposed. In a related area, the minimization of the duration of the locked-wheel condition during traction testing of heavy truck tires has been found necessary not as a result of traction sensitivities, per se, but rather as a result of the vertical load fluctuation that derives from even minor "flatspotting" (6). It has been observed, for example, that a single one-second lockup experience at rated load and 88 kph (55 mph) on dry pavement can result in a tire nonuniformity which introduces a threefold increase in the peak-to-peak fluctuations in vertical load. Since load fluctuations can become phased with the longitudinal slip transient so as to either support or diminish the peak traction which is realized, the minimization of the concentrated wear accruing during the locked-wheel condition is seen as a requirement in heavy tire testing.

Mobile Traction Dynamometers Employed at the Highway Safety Research Institute

By way of example concerning the preceding discussion of mobile apparatuses, the following is a presentation of two major apparatuses which have been employed by the Highway Safety Research Institute of The University of Michigan in research on tire pavement coupling. These devices are distinguished from one another by the tire type, either passenger car or truck, which is accommodated.

The HSRI mobile tester for passenger car tires consists of a retracting tire/wheel dynamometer mounted on a modified tandem-axle commercial tractor (Fig. 1). The mobile tire tester is designed to measure lateral and longitudinal tire forces, and aligning torques, on passenger car tires with vertical loadings between 90 kg (200 lbs) and 900 kg (2000 lbs). The device is designed for testing at speeds up to 112 kph (70 mph), sideslip angles up to 18 deg, and longitudinal slip ratios from -30% to +100%.

The test wheel assembly, including the force-balance system, is a modified version of the design used on the NASA Langley Research Center (4) tire-test vehicle. The most important modification is the addition of the test wheel speed control system which allows the test wheel to be operated at any value of wheel slip within the design range. Further, measurements can be made with test wheel speed at steady-state values of slip, or the wheel slip can be varied linearly or sinusoidally through a selectable range during a time interval variable from 3-7 sec.

The angular velocity of the test wheel is controlled by the hydraulic system of a variable displacement pump (driven by the power take-off of the vehicle) hydraulically coupled to a fixed displacement motor that drives the test wheel through a constant velocity universal joint and a right angle gear box. Shown in Figure 2, the drive shaft transmits drive (or braking) torques to the test wheel through flexible couplings which permit unrestrained motion of the dynamometer (relative to the test bed) over the full displacement range of its balance system. The tire dynamometer is attached to the test-bed through a ball spline mounted within a sleeve bearing that allows complete freedom of relative vertical movement. Constant vertical loading of the tire/wheel structure is maintained by an air spring which loads the floating spline member. The balance system consists of a built-up load cell mounted serially between the spline element and the wheel spindle assembly.

Figure 1. HSRI mobile tire tester for passenger car tires.

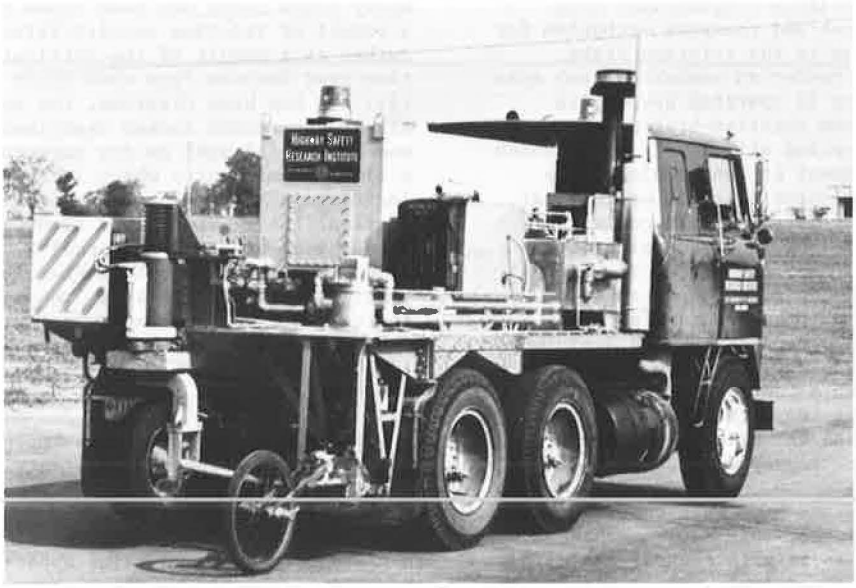
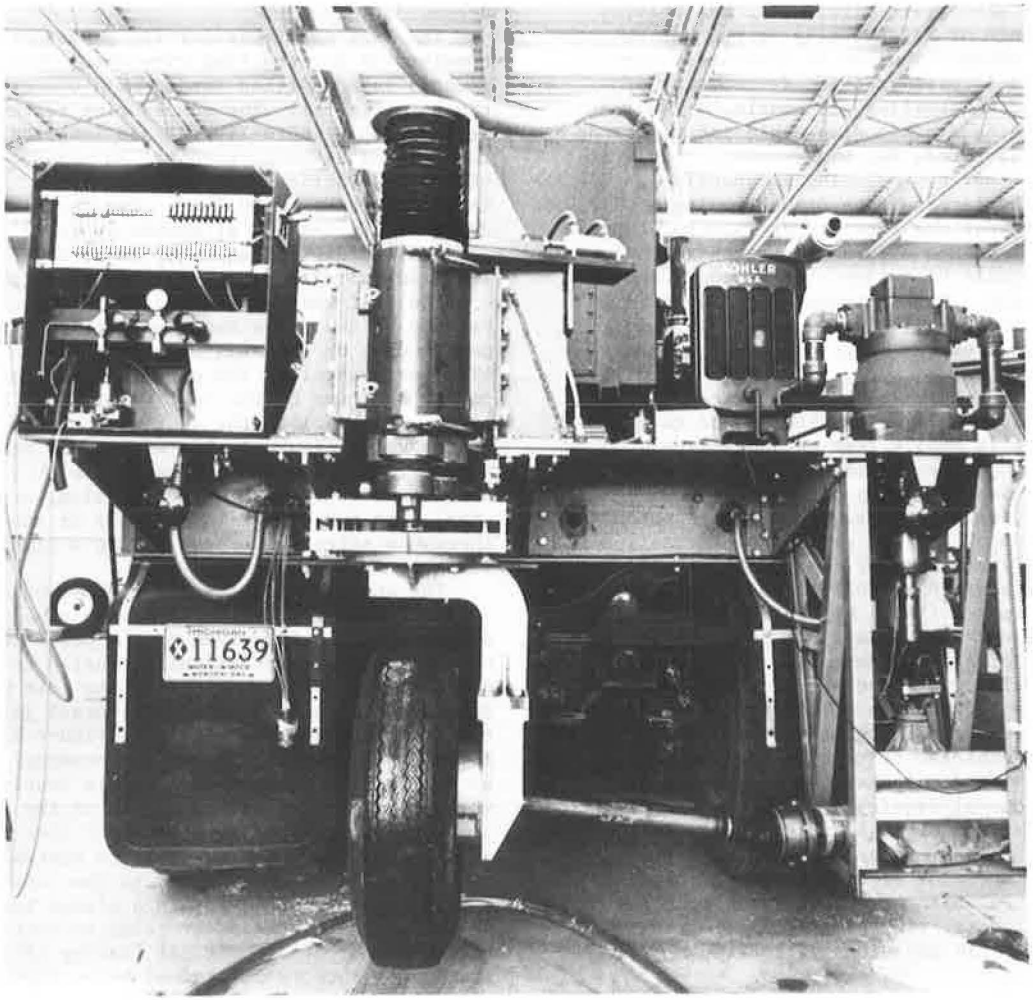


Figure 2. Rear view of test wheel drive system.



A second machine, the HSRI mobile truck tire dynamometer, consists of a tractor, semi-trailer vehicle which permits investigation of either longitudinal or lateral traction characteristics of heavy truck tires. The system, shown in Figure 3, permits measurement of longitudinal properties by way of the trailer-configured dynamometer as it is towed and serviced by the instrumented tractor. Mounted on the same tractor is a structure supporting a lateral traction measurement system. Each test system is basically designed to expose a truck tire specimen to a set of operating conditions which cover the full range of possible loads, velocities, longitudinal or angular slip, and pavements such as can be encountered under either normal or emergency situations on the highway.

The longitudinal traction dynamometer, shown in Figure 4, is a welded trailer structure of pipe and plate sections, designed for economy of construction and for stiffness. The test wheel is situated approximately at the trailer c.g. position and is supported by a parallelogram suspension, shown in Figure 5. The longitudinal force, F_x, vertical load, F_z, and brake torque, T_b, are transduced by way of a serially-mounted load cell. These signals, together with wheel angular velocity and vehicle velocity, constitute the primary data channels for the machine.

The nominal pitch and jounce trim of the HSRI trailer are controlled through the use of self-leveling air suspensions on both the trailer rear axle and the tractor rear tandem. Thus, as a given vertical load is transferred from the two respective axle sets to the test wheel, through inflation of the test wheel air spring, the tractor and trailer leveling systems adjust to a running equilibrium at which the trailer assumes its design trim attitude. The use of air suspensions on both ends of the trailer also contributes to attenuation of ride motions, thus further assuring quality in the vertical load condition.

The test trailer is capable of mounting any tire in the 51 cm (20 in) rim size, and above, which is:

a) Less than 117 cm (46 in) in free diameter, and
b) 46 cm (18 in) or less in maximum section width.

Tires can be loaded to a maximum level of 9,000 kg (20,000 lb), although to date, brake torque limitations have prevented the lockup of tires on high friction surfaces at loads exceeding about 7,000 kg (15,500 lb).

The lateral traction dynamometer shown schematically in Figure 6, mounts two tire samples on opposing steerable spindles outboard of the tractor's wheel tracks. The two tires are "toed-in" together by an electrohydraulic servo system covering a slip angle range from -1° to +30°. The test wheel spindles are mounted upon a solid cross-axle which is constrained by a single longitudinal pivot pin.

The pin itself is fastened within a cage which can move only vertically, as constrained by a set of four ball-spline bearings. The vertically-"floating" cage is then loaded through inflation of a set of air springs. Clearly, the "pivot axle" arrangement provides for a load equalization between both tires while also providing a higher frequency response to road profile irregularities which are uncorrelated, side-to-side. The "floating cage" provides the needed kinematic isolation of the vertical load from forces in the ground plane by virtue of its rectilinear antifriction constraints. The air spring loading configuration provides for precision load selection while incorporating a low spring rate coupling between the unsprung mass(es) and the foundation vehicle.

The two wheel spindles are "steered" to equal but opposing slip angles by an electrohydraulic servo system which incorporates two sets of

Figure 3. HSRI mobile traction dynamometer for truck tires.

Figure 4. Longitudinal force measurement trailer.

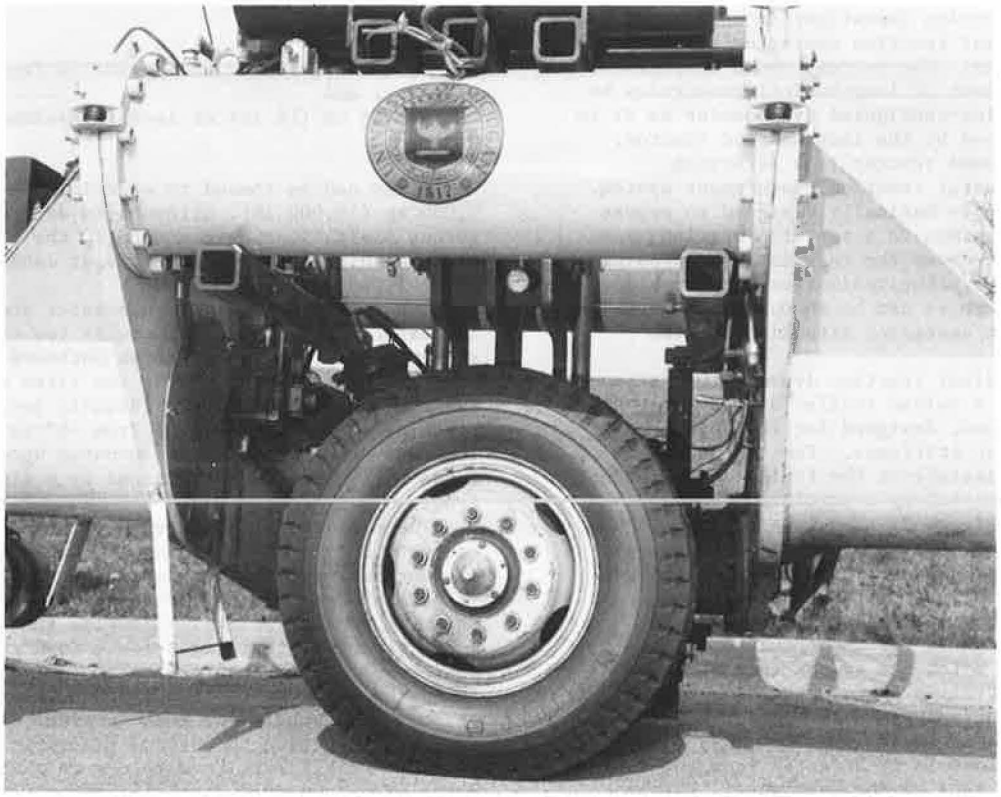


Figure 5. Parallelogram suspension of test wheel on the longitudinal force trailer.

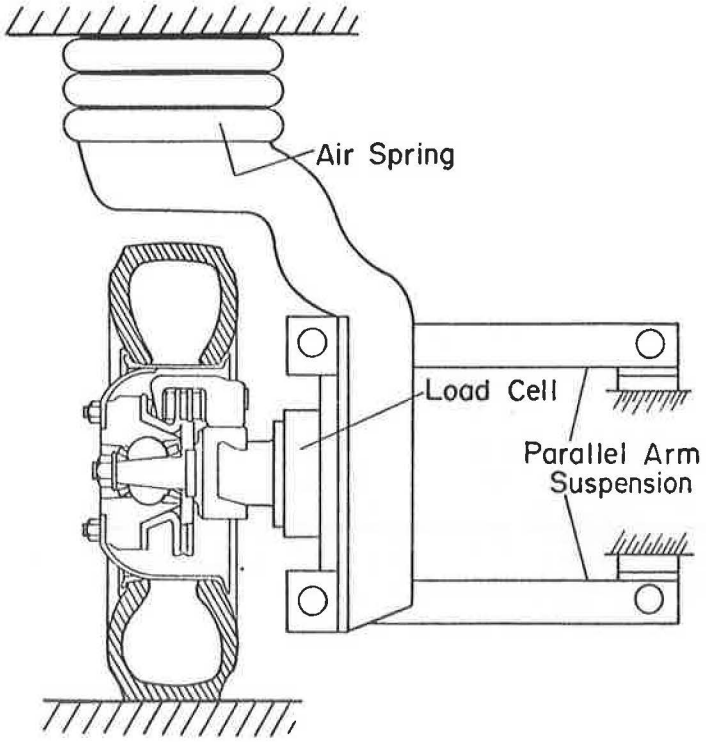
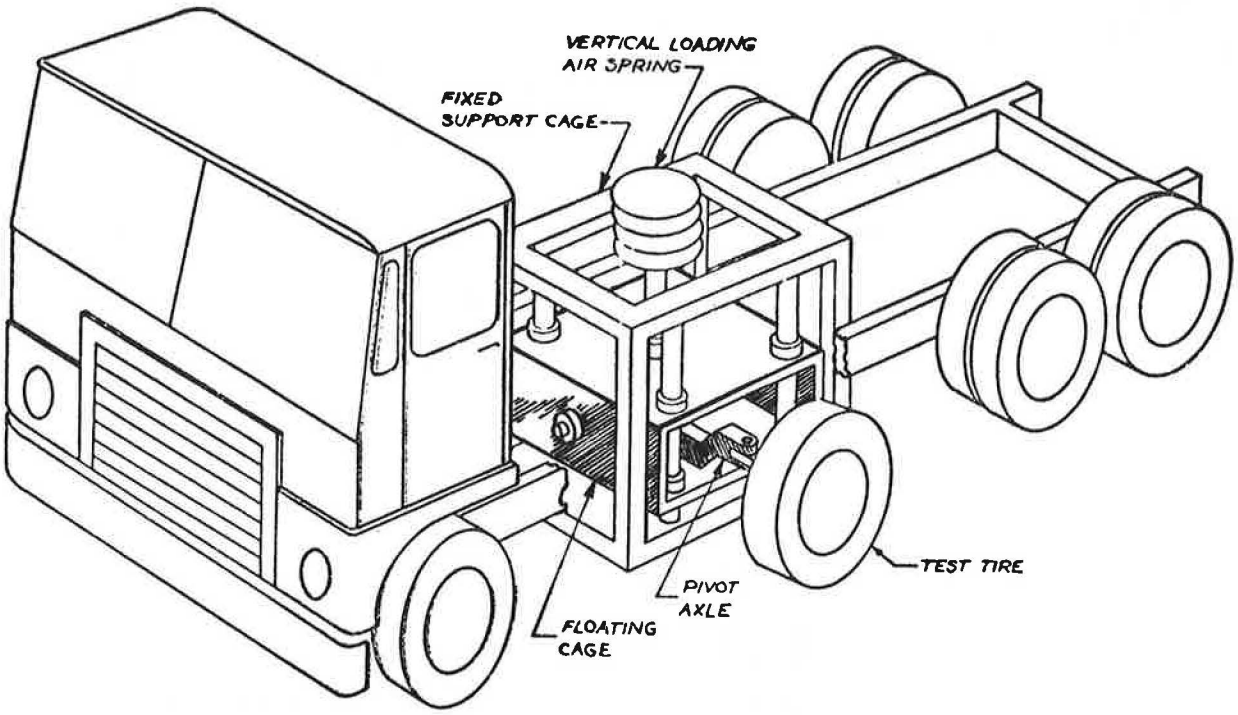


Figure 6. Major components of truck tire side force dynamometer.



actuating cylinders as shown in Figure 7. The linkage arrangement which mechanically couples both spindles together permits the use of a single control loop, operating on the feedback signal from the one instrumented wheel while assuring common slip angles, side to side, even in the event of a servo power failure.

The system permits mounting of any tire within the 76 cm (30 in) to 122 cm (48 in) range of free diameters and which is less than 46 cm (18 in) in cross-section width. The measurement of tire force and moment conditions is achieved by way of a serial multicomponent load cell which transduces lateral and vertical force components as well as aligning moment.

The overall mobile truck tire dynamometer incorporates a data acquisition and test control station shown in Figure 8. Mounted within a suspended module on the tractor, this system provides a controlled environment for instrumentation and permits the keeping of a handwritten log while underway.

Characteristic and Special Applications of Mobile Tire Testers

The characteristic usage of mobile tire traction dynamometers involves the comparative evaluation of a sample of specimens which exhibit at least one common parameter or design feature. Comparison testing typically involves the use of one or more selected surfaces which may be employed dry or wet or, perhaps, at various depths of water cover. This type of testing is typically not conducted on public roads. The measurements, if intended to comprehensively describe the high slip behavior of tires, would require that broad variations be made in both the velocity and vertical load conditions. In contrast to the basic nature of tire behavior near zero slip, shear force limits on either dry or wet surfaces are generally seen to exhibit significant sensitivity to velocity. Likewise, the normalized shear force limits on either wet or dry surfaces have been shown to be generally sensitive to the imposed load, although certainly not as a consequence of the same mechanisms as explain the load sensitivity of tire "stiffness" responses in the low slip regime.

Perhaps one of the more significant recent additions to the state of knowledge of shear force performance of tires on actual paved surfaces has been in the area of heavy truck tires for which, as stated earlier, no applicable test machinery existed until the early seventies. Insofar as mobile measurements of truck tire highway traction constitute a new development since the First International Skid Prevention Conference, a brief outline of the related findings may be suitable for inclusion here.

Recently published measurements of truck tire traction properties have revealed a number of longitudinal performance characteristics which differ markedly from the familiar behavior of passenger car tires. One dominant feature which has been seen in the μ-slip behavior of heavy truck tires is the large "falloff" in F_X/F_Z at high slip (i.e., beyond the peak traction condition), especially on dry pavements (8). A comparison of this characteristic with the corresponding behavior of a typical bias-ply passenger car tire (3) is indicated in Table 1. Here the ratio (peak F_X/F_Z)/slide F_X/F_Z) is

Figure 7. Section view of pivot axle.

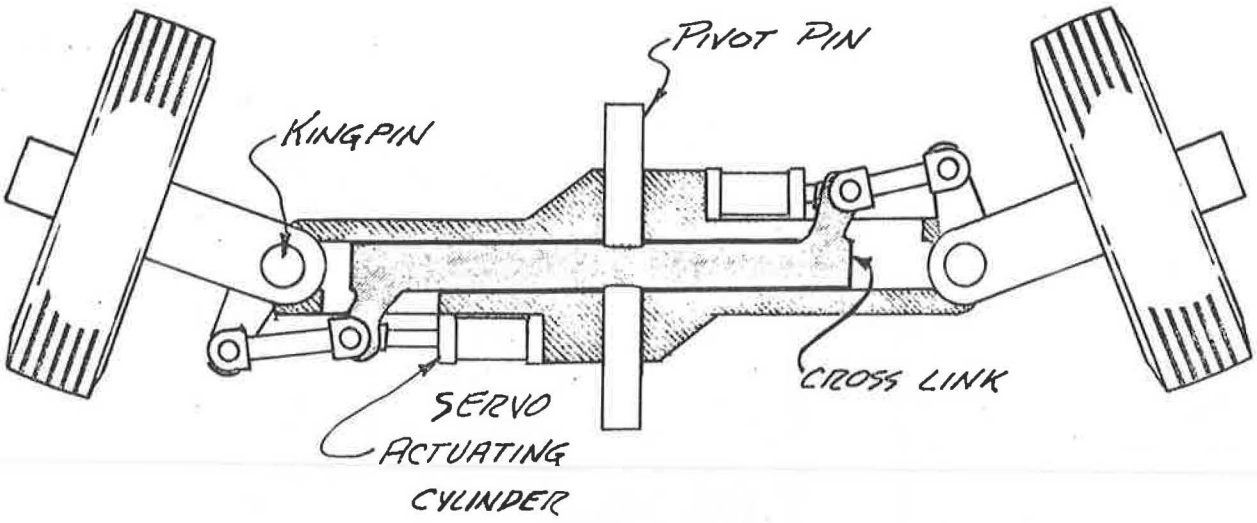


Figure 8. Data acquisition and test control station.

Table 1. Peak/slide ratios as influenced by velocity for typical car and truck tires of bias-ply construction (both tires operated at their rated loads on dry asphalt surfaces).

Tire	Velocities (km/hr) 8	16	32	64	88
Passenger Car Tire	1.23	1.24	1.20	1.08	1.00
Heavy Truck Tire	1.20	1.31	1.46	1.64	1.62

tabulated over a velocity range illustrating not only that the truck tire registers a much higher peak-to-slide falloff at highway speeds, but also that the trends between tire types are of the opposite polarity. In a similar vein, significant variations in longitudinal traction performance have been observed among the differing types of truck tire designs. As shown in Figures 9 and 10, the peak value of normalized longitudinal force, F_x/F_z, is seen to clearly discriminate on both dry and wet surfaces between bias-ply tires which are configured with circumferential rib-type tread patterns as opposed to cross lug-type treads. Based upon a limited number of samples (19), these data also show truck tires of the radial type carcass construction to yield a median level traction performance. These measurements, representing tires of the 10.00-20 size, also indicate that peak traction on dry surfaces is generally insensitive to velocity, although on a wetted, coarse macrotexture concrete, a substantial velocity sensitivity in peak F_x/F_z occurs. Other measurements which have been made of peak traction behavior also indicate a first-order sensitivity to vertical load, with F_x/Fz typically declining at a rate of .03 units per 454 kg (1,000 lb) of additional load in the vicinity of the tire's rated load.

Concerning locked-wheel traction performance of heavy truck tires, Figures 11 and 12 illustrate measurements taken on currently popular bias- and radial-ply tires in size 10.00-20. The data taken on a dry surface (Fig. 11) show a narrower overall spread of performance than was found in peak traction measurements. Further, there seems to be

Figure 9. Envelopes of peak longitudinal traction values obtained on dry concrete.

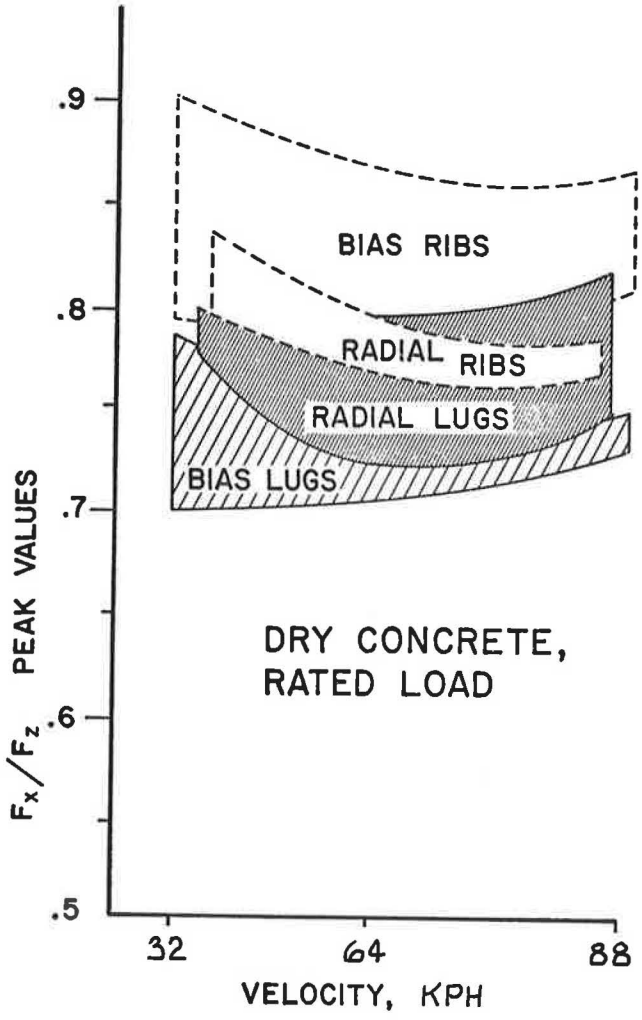


Figure 10. Envelopes of peak longitudinal traction values obtained on wet concrete.

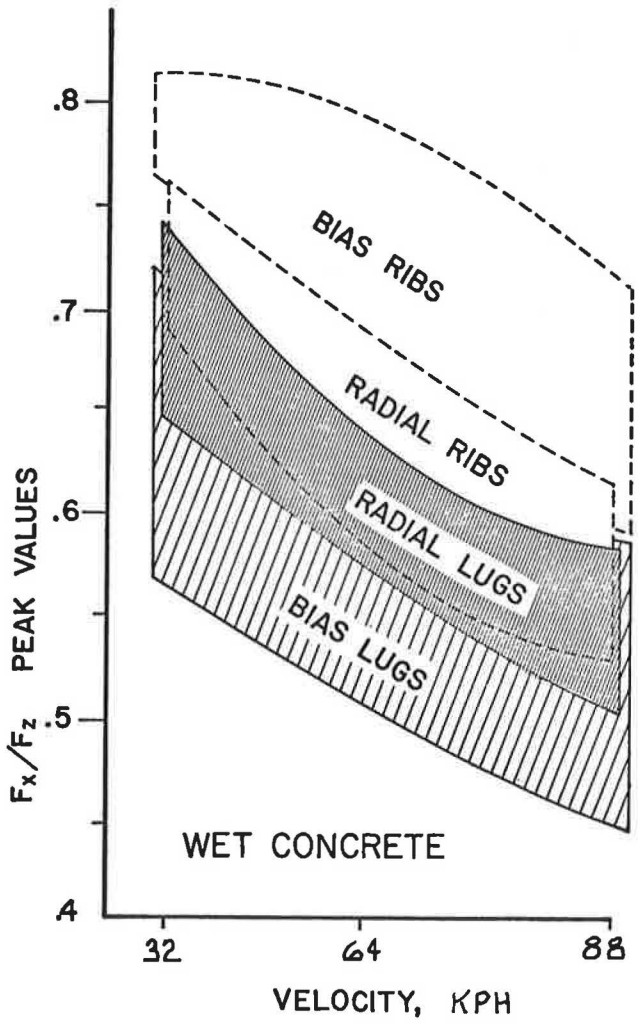


Figure 11. Envelopes of slide values of F_x/F_z obtained on dry concrete.

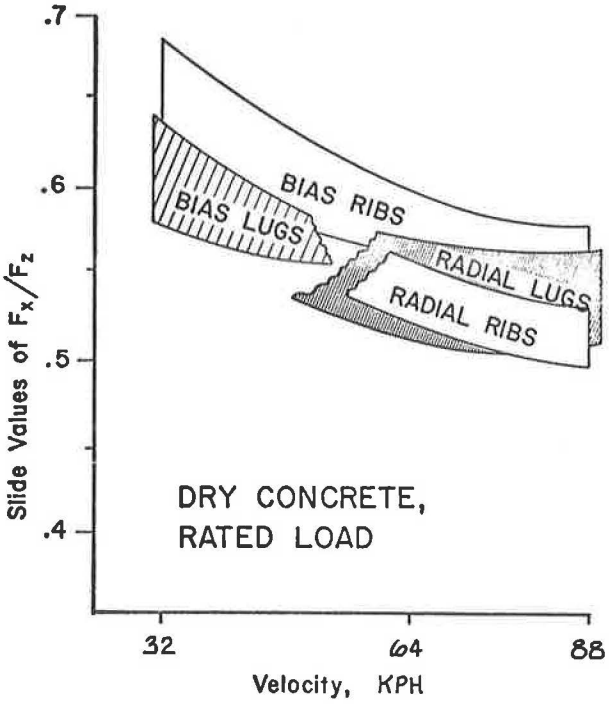
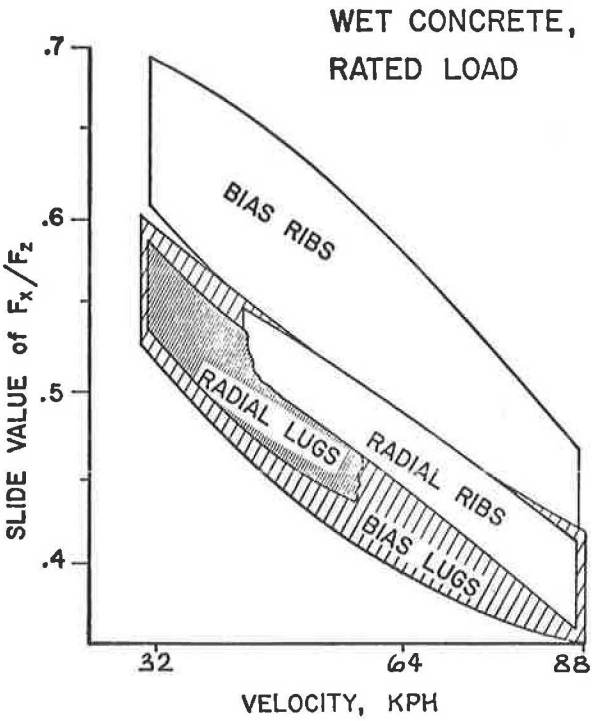


Figure 12. Envelopes of slide values of F_x/F_z obtained on a wet concrete surface.



little grounds for distinction in performance between individual tire carcass and tread constructions. The data taken on wet concrete, however, show (in Fig. 12) that the bias-ply, rib-tread tire again renders a superior slide traction performance over the other constructions which are identified. While the wet-slide data span a narrower range than the corresponding measurements taken on dry concrete, the slope of F_x/F_z with velocity clearly reveals the influence of a hydrodynamic mechanism.

Although, perhaps, of lesser interest because of the rollover (rather than lateral traction) limitation on heavy truck directional maneuvering, Figures 13 and 14 are presented to illustrate lateral traction behavior of heavy truck tires at high lateral slip. Plotting normalized lateral force, F_y/F_z, versus slip angle, α, these data show the performance range of a sample of common radial and bias-ply, rib and lug tread, truck tires. It is interesting to note that rib and lug tread patterns did not yield performances distinguishing one from the other. Also, we note that the lateral force response of the truck radial exhibits a higher initial slope, or cornering stiffness, leading to an "earlier" saturation in side force; that is, saturation occurs at lower values of slip angle with radial-ply tires. On the wet concrete surface, the data of Figure 14 illustrate a slightly higher lateral force capability for the average bias-ply tire. In general, available data indicate that the typical heavy truck tire possesses lateral traction properties rather similar to that of passenger car tires regarding normalized shear force level and regarding sensitivities to load and speed.

Figure 13. Envelopes of lateral traction performance on dry concrete.

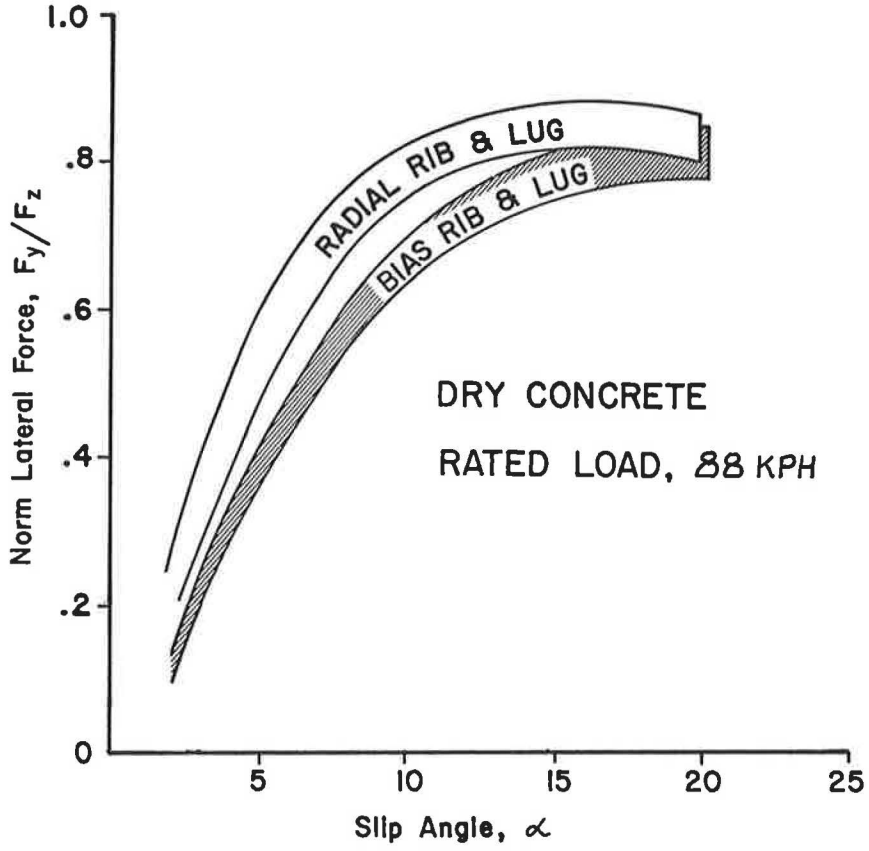
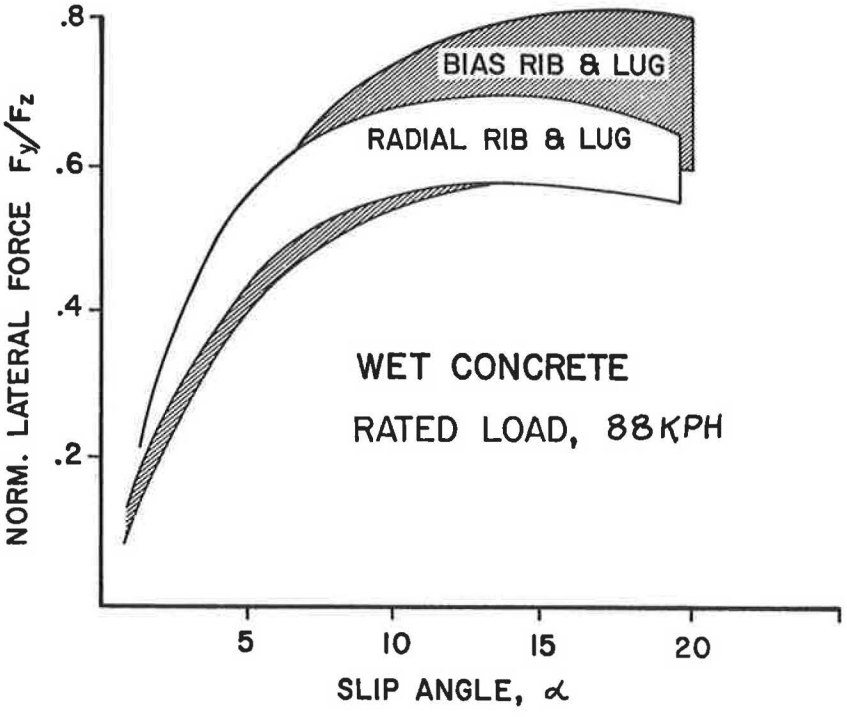


Figure 14. Envelopes of lateral traction performance on wet concrete.



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