

A Combined Cornering And Braking Test For Heavy Duty Truck Tires

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ABSTRACT

Under the auspices of the SAE Truck Tire Characteristics Task Force the background support for experimentally determining the combined cornering and braking properties of heavy duty truck tires has been developed. The purpose of the Recommended Practice will be to specify a standardized method for obtaining the combined cornering and braking data needed to represent tires in Vehicle Dynamics models.

This paper lays the proposed test procedure and background data before the technical community. The paper contains: a brief synopsis of the proposed test procedure, example data from CALSPAN and UMTRI taken using the proposed test procedure, a comparison of the CALSPAN and UMTRI data, and a discussion of how the proposed test affects tire free-rolling cornering properties.

INTRODUCTION

The purpose of the work reviewed in this paper is to establish a standardized testing procedure for producing combined cornering and braking tire force and moment data for use in vehicle dynamics simulations employed in the design and development of heavy duty trucks*. This work is part of a total project whose objective is to produce broadly accepted test procedures for three important tire operating regimes: free-rolling cornering, straight-line braking, and combined cornering and braking [1]**. The test procedures which are developed are to be expressed as SAE Recommended Practices (J-Documents).

This study was conducted as a SAE Cooperative Research project under the supervision of the Truck Tire Characteristics Task Force. The task force is composed of a group of engineers from the truck manufacturers, tire

* Heavy duty is taken to refer to all commercial over-the-road trucks and buses. For example, 18-wheelers, dump trucks, and school buses are included in heavy duty trucks as the term is used in this paper.

** Numbers in brackets refer to references listed at the end of this paper.

manufacturers, government, and testing organizations who are all interested in improving the ability of the engineering community to perform analytical design in support of good handling. Many members of this group helped with the work reported and are recognized in the Acknowledgments.

This project began with the synthesis of test procedures for free-rolling cornering, straight-line braking and combined cornering and braking tests. Then experimental evaluations for each procedure were designed. From these the Statement of Work [1] was assembled. Although development of three procedures is intended, this paper deals with only one of the procedures, the one for the Combined Cornering and Braking Test.

The task force chose to examine and compare the capabilities of the two public-domain pieces of equipment able to test heavy duty truck tires. One is at CALSPAN, and the other is at UMTRI.

All testing at CALSPAN was done using the large flat-surface TIRF machine, Figure 1. The TIRF machine has a single measuring station centered over a stainless steel belt. The measuring station is equipped with a five-component load cell for transducing tire forces and moments. The belt is coated with an emery cloth or sand paper to simulate pavement micro-texture. The steel belt is supported by an air bearing in the tire contact region and rotates on two 67 inch steel drums. All testing is conducted under computer control. The machine is capable of performing free-rolling cornering, straight-line braking, or combined cornering and braking tests on truck tires. The machine can also perform wet testing and has numerous other capabilities useful in testing passenger and light truck tires.

All testing at UMTRI was done on the Mobile Truck Tire Traction Dynamometer (herein, the Mobile Tire Tester, or the Mobile) shown in Figure 2. The Mobile Tire Tester consists of a long-wheelbase, three axle highway tractor towing a single axle semitrailer. The device has two test stations. A single test tire may be mounted on the centerline test station located at the mid wheelbase of the trailer. This test station is for brake force testing only and was not used in this project. The second test station is

based on a special axle mounted at mid wheelbase on the tractor. Free-rolling cornering, straight-line braking, or combined cornering and braking testing may be done at this test station. The wheels on the test axle run outboard of the nominal eight foot vehicle width. The spindle on the right side of the axle is equipped with a six-component load cell for transducing tire forces and moments. The spindle on the left is not transduced. The left tire serves only as a counteracting tire so that slip angles may be introduced by toeing the two tires toward each other while minimizing disturbance to the Mobile's path. Each wheel position is equipped with a very high capacity disk brake which allows aggressive braking programs with little concern for overheating.

Additionally, the task force chose to employ Smithers Scientific Services, Inc., as analysis contractor to analyze, summarize, and evaluate all data.

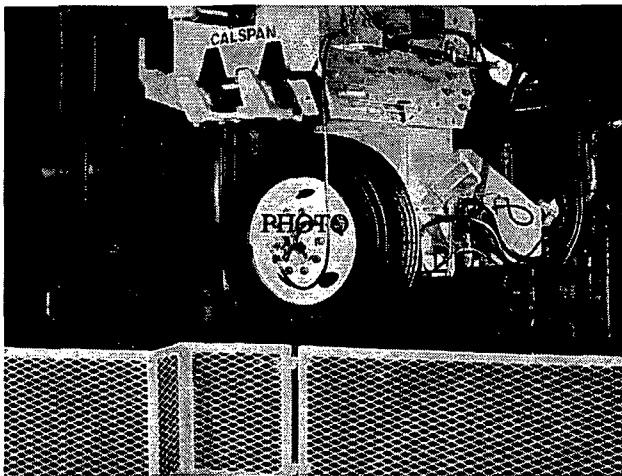


Figure 1. CALSPAN TIRF Machine

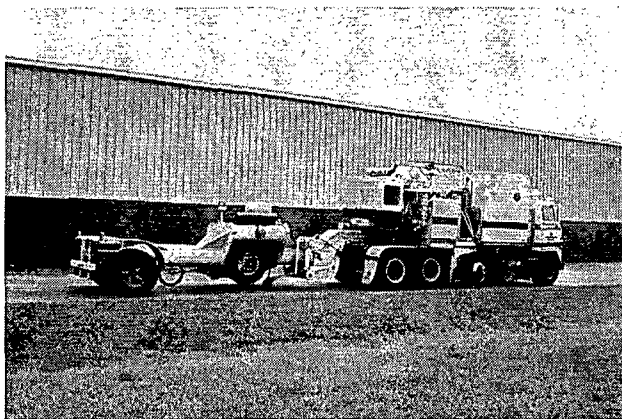


Figure 2. UMTRI Mobile Tire Tester

The task force specified that all work be done in customary (English) units since the majority of the target group is still working in these units. This paper follows the task force's direction.

The body of this paper begins with a brief discussion of the full test procedure developed in the project and applied by CALSPAN and UMTRI. Following the presentation of the procedure, the actual tire force and moment measurement results obtained by UMTRI and CALSPAN, and analyzed by Smithers, are presented. Conclusions are given at the close of the paper.

TEST PROCEDURE

The test procedure has not yet been formally arranged in the format used in a recommended practice. Instead this section gathers together those elements which will be formally assembled by a specially appointed task force.

TWO CAUTIONS

1. Tire force and moment properties change significantly over time as tires age [2]. Therefore, test tires must be stored under equivalent or well understood conditions to prevent invalid judgements. Either vehicle models or tests using tires of very different ages or tires stored at very different temperatures cannot be taken as representing a true comparison of the tire specifications being studied.

2. Ambient temperature during testing influences tire force and moment properties [3]. Strict control is desirable. However, practical productivity problems in over-the-road force and moment testing require establishment of an ambient temperature range. 60°F to 80°F (16°C to 27°C) was chosen for this work. This limits the expected temperature associated F_y error to less than $\pm 2\%$.

INFLATION PRESSURE

Tire force and moment properties are strong functions of inflation pressure. Therefore, we chose an inflation pressure representative of actual tire service for the tire specification under test rather than an arbitrary pressure. This pressure was determined through a small pretest based on experience with heavy duty tires. The procedure follows:

1. Mount the experimental tire on the test rim specified by the appropriate tire and rim standards organization.*
2. Inflate the tire to the target cold inflation pressure specified by the test requester and cap the valve.
3. Run the tire for one hour at the following conditions: inclination angle (γ) = 0 degrees; slip angle, α = 0 degrees; normal force (F_z) = -(rated load for the target cold inflation); and specified test speed (S) for one hour.
4. At the end of 1 hour stop the tire and measure the inflation pressure (P).** P is the inflation pressure that will be used during tire conditioning and test.

PRE-TEST CONDITIONING

The cornering properties of tires are dependent on tire operating temperature, tire wear state, and the exercise state of the tire materials, as well as the intrinsic properties of the tire as manufactured. The pre-test conditioning was

* The Tire and Rim Association is an example.

** CALSPAN and UMTRI results were nearly identical.

designed to assure thermal equilibration of the test tire and produce a modest, consistent exercise of a new tire prior to actual testing. The purpose of the pre-test is to simulate the condition a new tire is apt to exhibit after a few hours of highway usage..

The pre-test conditioning procedure is as follows:

1. Mount the experimental tire on the test rim specified by the appropriate tire and rim standards organization.
2. Inflate the tire to the test inflation pressure (P) using a pressure regulator which stays in effect throughout pre-test conditioning and the cornering and braking test itself.
3. Load the tire at $F_z = -$ (rated load for the target cold inflation).
4. Operate the test tire in accordance with the instructions in Table 1. Speed, S, is at the discretion of the tester, but should be maintained throughout the entire test sequence. *
5. Maintain $\gamma = 0.0$ degrees.

Table 1. Pre-test Conditioning Steps

Step	Distance	α , degrees
#1	S X 1 hr.	0.0
#2	0.5 mi. (0.8 km)	1.0
#3	0.5 mi. (0.8 km)	-1.0

WARM-UP IN CASE OF A BROKEN TEST

If a test must be stopped because of an equipment problem or other limitation, not due to a tire problem, the tire shall be warmed up at S for one hour at $\alpha = \gamma = 0.0^\circ$ with inflation pressure and normal force as specified in the pre-test conditioning before testing is resumed.

FORCE AND MOMENT MEASUREMENT

Immediately following pre-test conditioning, without stopping, measure the tire force and moment response according to the following test matrix specification. (See the following section for a full description of the data to be acquired.) The sequence is: set the first F_z , perform the braking ramp at each member of the α sequence in order, set the second F_z , perform the braking ramp at each member of the α sequence in order, and so forth until completion.

The procedure for a single tire is as follows:

1. Inflate the tire to the Test Inflation Pressure (P) using a pressure regulator.
2. Maintain $\gamma = 0.0$ degrees.
3. Maintain Test Speed (S).
4. Test in this F_z sequence. $F_z = -25, -50, -75, -100, -125, -150, -200$ percent of the Rated Load for the specified cold inflation pressure.
5. Use this α sequence within each F_z step. $\alpha = +\alpha, -\alpha$.**

* S = 45 mph (72 km/hr) was used in the work reported in this paper to fit the characteristics of the Mobile and the test site.

** Each tire had a different Slip Angle set for wear reasons. Experience indicates that this requirement can be relaxed as noted later. The sets were: $\pm 1^\circ, \pm 2^\circ, \pm 4^\circ, \pm 6^\circ$.

6. At each normal force/slip angle combination the tire is to be braked from a slip ratio of 0.00 to a slip ratio of -0.80 at a rate of -0.80/sec.

DATA ACQUISITION AND REPORTING

During each test step data is to be recorded at such a rate as to provide data at least at every 0.01 increment of slip ratio for the following listed variables: $F_x, F_y, F_z, M_x, M_z, IA, R_1,$ and SA.*

CONTROL TIRE PROCEDURES

It is very important to verify that the slip angle gain and zero are constant. It is also important to record the frictional history of the test surface or surfaces used. Without these data it is impossible to confirm that a stable relationship exists between test machine/surface combinations or to even be sure that measurements for the same test machine/surface combination correlate with one another as time passes. The preceding paper in this series [4] discusses the required control tire procedures in detail.

LIMITATIONS OF THE TEST EQUIPMENT

Both the CALSPAN and UMTRI test machines have mechanical limitations. Those which could impede combined cornering and braking tests performed according to the test procedure in this report are listed below. Please note that other limitations may become crucial in tests done according to different test procedures. Those other limitations which may affect free-rolling cornering or straight-line braking tests will be considered in other papers in this series.

CALSPAN

These are the limitations of the CALSPAN machine as perceived at the time the work being reported was done.

1. Inflation Pressure: None so long as values are consistent with the requirements of the appropriate tire and rim standards organization.
2. Test Speed: None from normal highway speeds downward. Speeds of up to 200 mph (320 km/hr) are possible on the TIRF machine.
3. Tire Diameter: 47 inches (1195 mm) maximum.
4. Tread Width: 24 inches (610 mm) maximum.
5. Inclination Angle: None which affect this procedure.
6. Slip Angle: None which affect this procedure.
7. Forces: $F_x, -7,500$ lbs. (-33,400 N) $< F_x < 7,500$ lbs. (33,400 N). This limit is associated with the belt drive and the relationship between the kinetic energy in the system, the capacity of the drive, and the rate at which the braking event drains energy from the system. The quoted limit is for

* Definitions are in the nomenclature section.

the test discussed in this paper. The force measuring balance has a capacity of 9,000 lbs. (40,000 N).

F_y , -8,000 lbs. (-35,600 N) $< F_y < 8,000$ lbs. (35,600 N).

F_z , -10,000 lbs. (-44,500 N) $< F_z < 0$ lbs. This does limit the load on Testable tires.

8. Moments: M_x , none affecting this procedure.
 M_z , -2,000 ft.-lbs. (-2,700 N-m) $< M_z < 2,000$ ft.-lbs. (2,700 N-m).

UMTRI*

These are the limitations of the UMTRI machine as perceived at the time the work being reported was done.

1. Inflation Pressure: None so long as values are consistent with the requirements of the appropriate tire and rim standards organization.
2. Test Speed: $S < 60$ mph (96.5 km/hr) all conditions. May be further limited due to a combination of roadway geometry and engine power. Acceleration beyond 45 mph (72 km/hr) is time consuming. If F_x is very large, the truck will slow rapidly.
3. Tire Diameter: 54 inches (1372 mm) maximum in standard configuration. The brake disc diameter limits testable tires to rolling radii greater than 19 inches (483 mm).
4. Tread Width: 19 inches (483 mm) maximum in standard configuration.
5. Inclination Angle: None which affect this procedure.
6. Slip Angle: None which affect this procedure.
7. Forces: F_x , -15,000 lbs. (-66,700 N) $< F_x < 0$.
 F_y , none affecting this procedure.
 F_z , -15,000 lbs. (-66,700 N) $< F_z < 0$ lbs. With special ballast F_z may reach -20,000 lbs. (-89,000 N).
8. Moments: M_x , none affecting this procedure.**
 M_z , none affecting this procedure.

TIRE MEASUREMENT RESULTS

The following sections discuss the results of the measurement programs conducted by CALSPAN and UMTRI for this project. The discussion addresses the general functional form and the repeatability of the measurements, a

* Since the UMTRI Mobile is an over-the-road device based on a truck chassis, it is affected by wind, tire pull forces, road camber, and road roughness. In addition slip angle and normal force are open loop control systems. Therefore, significant scatter is to be expected in the data.

** The M_x results are not of good quality [4]. There is an apparent offset.

comparison of the CALSPAN and UMTRI data, and a discussion of how the proposed test affects the tire free-rolling cornering properties.

TEST TIRES

All test tires were 295/75R22.5 drawn at random from a 200 tire lot taken from a single day's production of the AMERI*S380 LP steer axle tire by General Tire.

TEST SURFACES

The test surfaces used by CALSPAN and UMTRI are inherently different. This affects all the data and should be borne in mind at all times while examining the tire measurement results.

CALSPAN must use an abrasive paper or an emery cloth as a friction surface due to the necessity of having a flexible surface on the steel belt roadway which passes around the machine drums.

In this project, it was intended that CALSPAN use 120 Grit 3Mite[®] Aluminum Oxide material as the test surface. However, some of the tests were run on 80 and 120 Grit 3M Polycut[®] a longer lasting Ceramic Oxide material which was thought to offer long time stability for the friction surface.

UMTRI may use any conventional road surface on which they can run the Mobile Truck Tire Dynamometer.

In this project UMTRI used the Dana Corporation track at Ottawa Lakes, Michigan, which is concrete.

A very significant surface effect showed in the UMTRI and CALSPAN data as slip increased above magnitudes of 0.06 to 0.10. This was not a problem in the free-rolling cornering data [4], but was easily seen in the longitudinal force (F_x) data from the straight line braking test [5] and in the combined cornering and braking data [6]. The pertinent part of these results will be discussed in the section comparing the CALSPAN and UMTRI data.

DATA FUNCTIONAL FORM AND REPEATABILITY

This section deals primarily with lateral force, aligning moment, and overturning moment with only a few comments on longitudinal force repeatability.

F_x , Longitudinal Force The functional form of the longitudinal force was as expected and will be discussed in detail in a later paper devoted to the straight-line braking test. However, there is an important difference in repeatability for longitudinal force in the combined cornering and braking tests done at CALSPAN [6] and in the straight-line braking tests done at CALSPAN [7]. As shown in Table 2, the longitudinal force standard deviation is load (normal force) dependent in the combined cornering and braking case, but not in the case of straight-line braking. Further, the standard deviations are much larger in the combined case. The only reasonable explanation is that a load cell interaction occurs in the presence of slip angle, α , which is not present in straight-line braking.

The longitudinal force standard deviation results at UMTRI are load independent and comparable in magnitude for combined cornering and braking, 192 lbs. (854N), and

for straight-line braking, 278 lbs. (1,236 N). The difference is reasonable considering that there are nine times as many data points in the combined case results as in the straight-line braking results.

Table 2. F_x Standard Deviations

% Rated Load	Standard Deviation, lbs. (N)	
	Straight-Line	Combined
50.0	132 (587)	97 (431)
100.0	132 (587)	191 (850)
150.0	132 (587)	285 (1268)

F_y , Lateral Force The form of the lateral force as a function of slip ratio at each load and slip angle is as expected [6, 8]. Figures 3 and 4 show $\alpha = \pm 6^\circ$ results for CALSPAN and UMTRI respectively. Both figures are

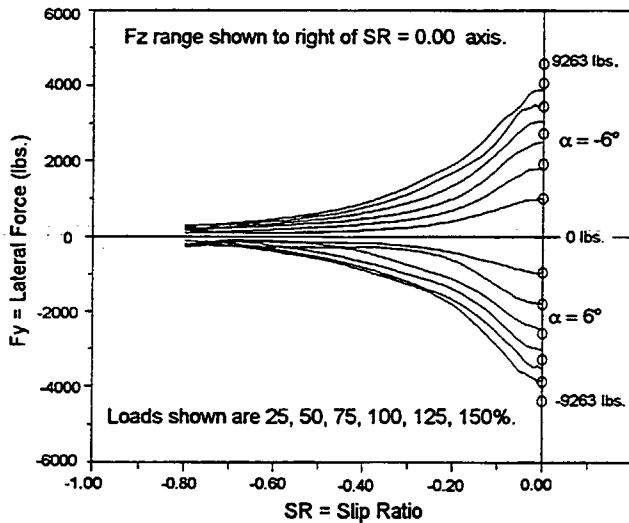


Figure 3. Lateral Force by CALSPAN vs. Slip Ratio

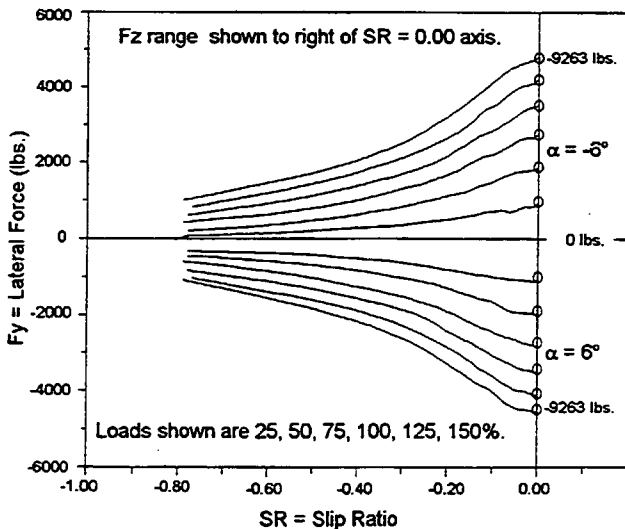


Figure 4. Lateral Force by UMTRI vs. Slip Ratio

connect-the-dot, that is, the results for all 81 slip ratio values at a given load and slip angle were connected with short straight line segments. The data points from the combined case testing are not shown to reduce clutter. The large circular points on the vertical axes are from the free-rolling test [4]. At zero slip ratio the combined case results should match the free-rolling cornering results. This is a measure of data quality.

The CALSPAN results are the average of data from four tires.

The UMTRI results are the average of data from five tires.

Examination of the total set of results [6, 8] reveals three interesting points.

1. Neither machine yields valid F_y data at zero slip angle when operating in the braking mode.
2. The CALSPAN F_y results in the combined mode for lateral force magnitudes greater than about 2,500 lbs. (11,100 N) at zero slip ratio are smaller than those achieved in the free rolling case.
3. Outside the range, $-1^\circ \leq \alpha \leq 1^\circ$, within which its accuracy limitations produce some offsets between different data sets*, the UMTRI machine produced closely comparable F_y in both the combined case at zero slip ratio and in free-rolling cornering.

The standard deviations for the CALSPAN and UMTRI lateral force data from the combined cornering and braking test are presented in Table 3. For both machines, standard deviation is dependent on normal force. This was also true in the free-rolling cornering case.

The order of magnitude for the standard deviations obtained in the combined case at CALSPAN is about double that found in the free-rolling case which is represented by a pooled standard deviation of 27.2 lbs. (121 N). The order of magnitude for the standard deviations obtained in the combined case at UMTRI is about the same or a bit less than that found in the free-rolling case represented by a pooled standard deviation of 124.5 lbs. (554 N). As noted earlier, the indoor, TIRF, machine is a more precise device.

Table 3. F_y Standard Deviations

% Rated Load	Standard Deviation, lbs. (N)	
	CALSPAN	UMTRI
50.0	27.8 (124)	76.6 (341)
100.0	45.5 (202)	95.0 (423)
150.0	63.2 (281)	113.4 (504)

The lateral force data from combined cornering and braking tests is often plotted as a graph of lateral force versus longitudinal force rather than as lateral force versus slip ratio plots as was done in Figures 3 and 4. Figure 5 is a F_y versus F_x plot, friction ellipse, for a sample of the UMTRI data.

* These offsets arise due to pull forces which cannot be resolved accurately by the UMTRI mobile tester.

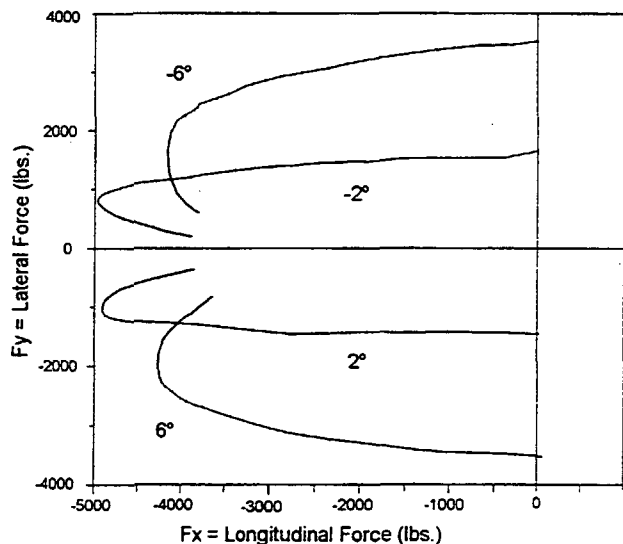


Figure 5. UMTRI Lateral Force vs. Longitudinal Force at Rated Load

M_x , Overturning Moment Earlier, in discussing the limitations of the two machines, we noted that the UMTRI machine was not suitable for use in the determination of overturning moment based on the earlier work done on free-rolling cornering [4]. That conclusion continues to be borne out in the combined cornering and braking case. Surprisingly, the CALSPAN machine which is quite acceptable in the free-rolling case exhibits large variation in this case. Figure 6 shows the individual tire data and connect-the-dots average lines for the rated load condition at $\alpha = \pm 6^\circ$. Neither machine is a suitable source of over-

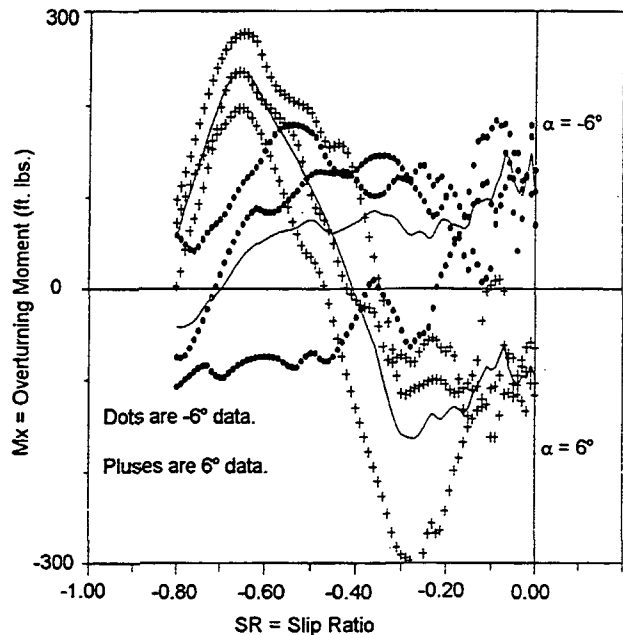


Figure 6. CALSPAN Overturning Moment Scatter

turning moment data in the case of combined cornering and braking.

M_z , Aligning Moment The form of the aligning moment as a function of slip ratio at each load and slip angle is shown in Figures 7 and 8 for CALSPAN and UMTRI respectively. Both figures are connect-the-dot, that is, the results for all 81 slip ratio values at a given load and slip angle were connected with short straight line segments. The data points from the combined case testing are not shown to reduce clutter. The large circular points on the vertical axes are from the free-rolling test [4]. At zero slip ratio the combined case results should match the free-rolling cornering results. This is a measure of data quality.

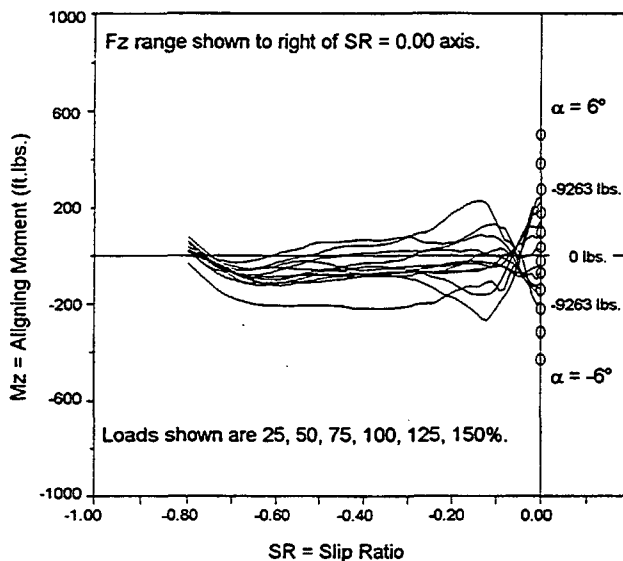


Figure 7. Aligning Moment by CALSPAN vs. Slip Ratio

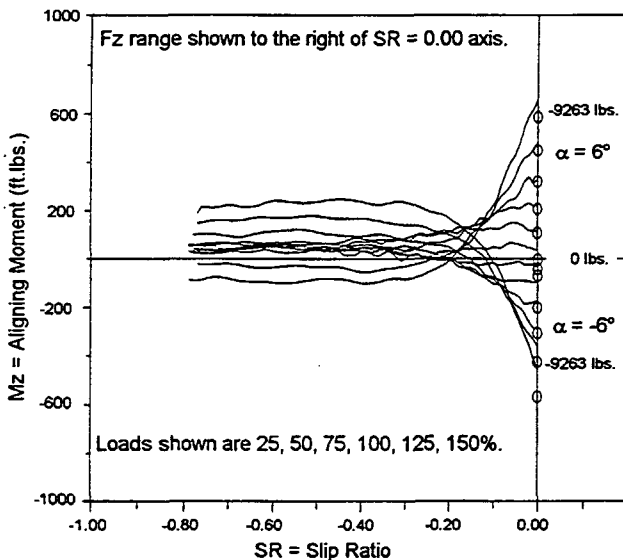


Figure 8. Aligning Moment by UMTRI vs. Slip Ratio

The CALSPAN results are the average of data from four tires.

The UMTRI results are the average of data from five tires.

Examination of the total set of results [6, 8] reveals four interesting points.

1. Neither machine yields valid M_z data at zero slip angle when operating in the braking mode.
2. The CALSPAN M_z results quickly cross zero as slip ratio magnitude increases. This is not an expected result.
3. The CALSPAN M_z results in the combined mode at zero slip ratio are smaller than those achieved in the free rolling case as slip angle increases becoming about half of the free-rolling result at 6° slip angle.
4. The UMTRI machine produced closely comparable M_z in both the combined case at zero slip ratio and in free-rolling cornering.

It is suspected that an interaction effect exists in the CALSPAN measuring system which is not accounted for in the machine calibration.

The standard deviations for the CALSPAN and UMTRI aligning moment data from the combined cornering and braking test are presented in Table 4. For both machines, standard deviation is dependent on normal force. This was also true in the free-rolling cornering case.

The order of magnitude for the standard deviations obtained in the combined case at CALSPAN is about 14 times that found in the free-rolling case which is represented by a pooled standard deviation of 3.8 ft.lbs. (5.2 N-m). The order of magnitude for the standard deviations obtained in the combined case at UMTRI is about 1.5 times that found in the free-rolling case represented by a pooled standard deviation of 23.8 ft.lbs. (32.3 N-m).

Due to the unusual character of the CALSPAN M_z data in combined cornering and braking and the significant increase in variance in combined cornering and braking, use of the CALSPAN M_z data from a combined cornering and braking test proposed is not recommended.

Table 4. M_z Standard Deviations

% Rated Load	Standard Deviation, ft.lbs. (N-m)	
	CALSPAN	UMTRI
50.0	53.4 (72.4)	27 (36.6)
100.0	71.6 (97.1)	34.5 (46.8)
150.0	89.8 (121.8)	42.1 (57.1)

Fundamental Observations Table 5 lists the forces and moments from the combined cornering and braking test which have been judged to be of usable quality. This judgment is based on the force and moment functional form and repeatability discussion. Only longitudinal force and lateral force from both machines are of such quality as to make an attempt at machine correlation worthwhile in the combined cornering and braking case. Correlation for F_x and F_y is briefly examined later in the paper after the question of how many tires to test is explored for those forces and moments where usage is recommended in Table 5.

Table 5. Usable Force and Moment Results for Combined Cornering and Braking Test

Component	Usable (Yes or No)	
	CALSPAN	UMTRI
F_x	Yes	Yes
F_y	Yes	Yes
M_x	No	No
M_z	No	Yes

THE NUMBER OF TIRES NEEDED IN A SAMPLE

The engineer always wants to know how many tires to include in test samples in order to have a valid expectation of being able to detect a given difference between tire specifications at a pre-defined level of confidence. For those forces and moments defined as usable in Table 5, it is possible to prepare charts relating sample size required to detect a pre-defined difference between sample means at a pre-chosen level of confidence [9]. Figure 9 is provided here as an example. Figure 9 is the chart which pertains to F_y for tests on the UMTRI Mobile Tester. It is based on the worst variance situation, highest load.

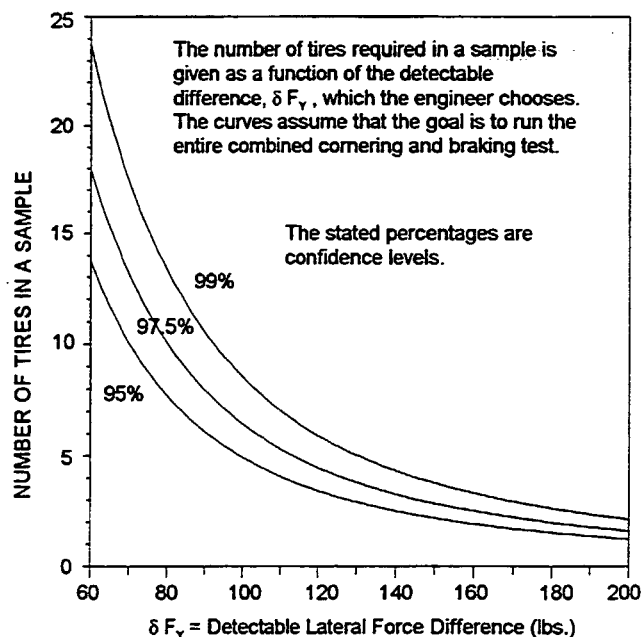


Figure 9. UMTRI F_y Sample Size Selector Chart

CALSPAN TO UMTRI CORRELATION

In the section on test surfaces we noted the marked difference between the test surfaces used by CALSPAN and UMTRI and noted that this difference was not a major concern in the case of free-rolling cornering at small slip angles, $|\alpha| \leq 6^\circ$. In the combined cornering and braking case [9] and straight-line braking case [5] the surface difference is very important. Indeed, the data which will now be presented show that there is a very real need to provide indoor test surfaces with a known correlation to one or

more commonly used outdoor test surfaces. It is well recognized that outdoor surfaces are not stable over time [10]. Therefore, any indoor surface which would be endorsed as "correlated" to an outdoor surface would really represent only a reasonable approximation to the behavior to be expected on the target outdoor surface at a given moment of time. It is also well recognized that stability of the indoor surface should be monitored over time. A good example of the importance of this appeared in the straight-line braking portion of this program [7].

F_x , Longitudinal Force Figure 10 shows CALSPAN longitudinal force, F_x , as a function of UMTRI F_x . The fishhook like curves that result as the data are plotted against each other slip ratio by slip ratio are relationships not functions, thus, no general simple correlation exists between the F_x values on the two machines. There are other

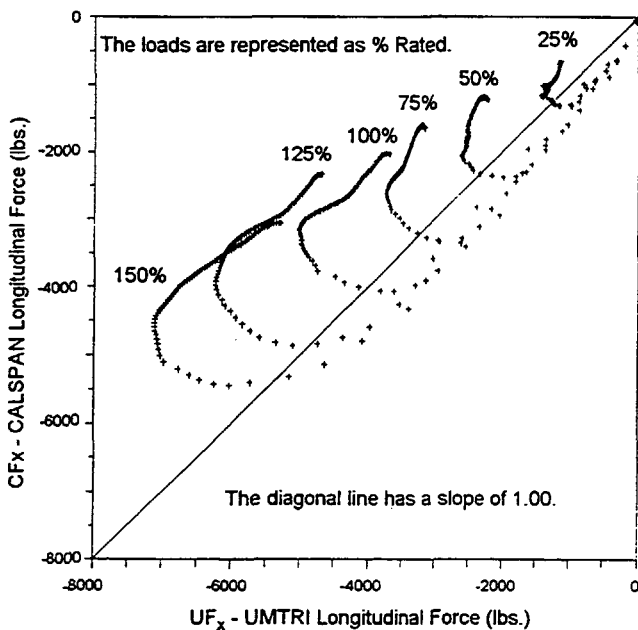


Figure 10. CALSPAN/UMTRI F_x Correlation

effects which can be seen as the F_x correlation is explored further [5]. These will be discussed in a later paper.

F_y , Lateral Force It is theoretically possible to construct a correlation between CALSPAN lateral force, F_y , and UMTRI F_y if slip angle and normal force are included as parameters [9]. It is not possible to produce a simple correlation involving only CALSPAN and UMTRI lateral forces. By way of example, Figure 11 shows the correlation for rated load. The data points are the average test results plotted slip ratio by slip ratio. The curves are cubics in F_y which are functions of slip angle. The curves differ as load changes. Given the complexity in this situation, we suspect that a CALSPAN/UMTRI correlation equation if fully developed might not be general, independent of tire size and construction.

Fundamental Observation Data from the CALSPAN and UMTRI machines are not correlated for the combined cornering and braking test. Since vehicle behavior is dependent on the balance of data among the various tires, it is inappropriate to mix combined cornering and braking from both machines in a single vehicle dynamics model.

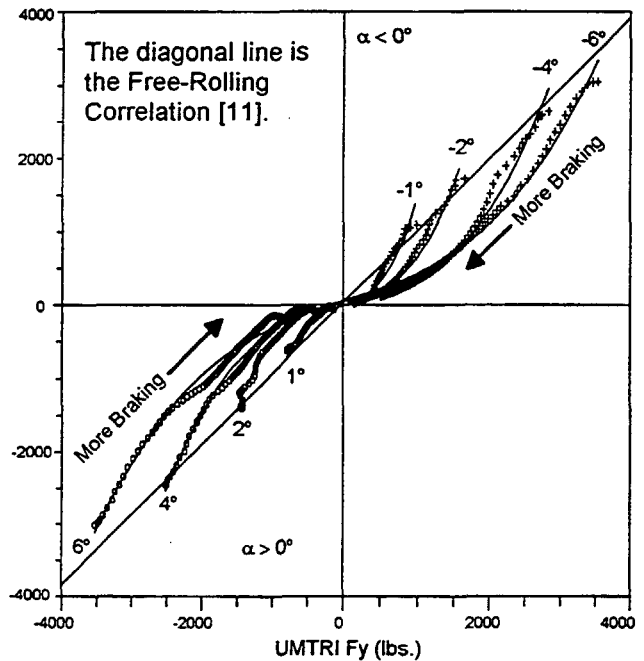


Figure 11. CALSPAN/UMTRI F_y Correlation

TEST EFFECT ON FREE-ROLLING CORNERING

Since testing changes tire force and moment properties a feature of the experimental design [1] was a check test of the free-rolling cornering properties at the end of the each tire test. The thought was that if the check revealed little or no change in properties due to the test then the test gives a valid representation of the tire's properties. A big change would indicate that the results were as much test artifacts as tire properties. The check was done without stopping after the combined test. The check test was performed at rated load with $\alpha = \pm 1^\circ, \pm 4^\circ$.

The results of the check test were compared to the results of the free-rolling cornering test [12, 13]. This was done for F_y and M_z from both machines and for M_x for the CALSPAN machine in Reference 14. Figure 12 is an example comparison.

Fundamental Observation The set of comparisons indicates that the test as designed does not grossly alter tire force and moment properties. Therefore, the results are probably representative of actual tire properties subject to the limitations due to measuring machine properties and test surfaces which have just been discussed. It may be that a test tire could be used for more than one \pm set of slip angles, but proving this would be a costly process.

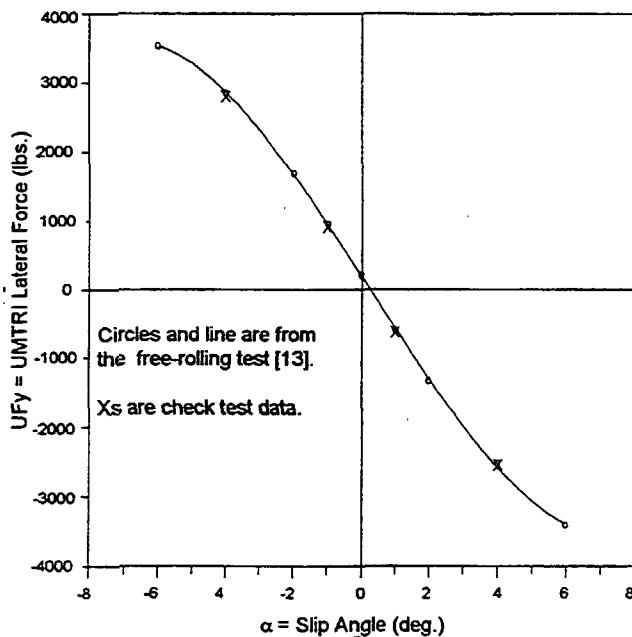


Figure 12. Effect of Combined Procedure on F_y , UMTRI Data

CONCLUSIONS

1. The combined cornering and braking test proposed in this paper is usable for its intended purpose.
2. The test does not appear to significantly change tire force and moment properties.
3. CALSPAN and UMTRI combined case data should not be combined in a single vehicle dynamics model.
4. CALSPAN and UMTRI combined case lateral force data are not correlated in any simple way.
5. CALSPAN and UMTRI combined case longitudinal force data are not correlated. There is an important surface friction effect.
6. CALSPAN and UMTRI combined case overturning moment data are not usable.
7. CALSPAN combined case aligning moment data is not usable.

ACKNOWLEDGMENTS

There are many people and organizations who helped to make this work possible. Funding was through National Highway Traffic Safety Administration Contract No. DTNH22-92-C-17189 awarded to Society of Automotive Engineers Cooperative Research. The funds were assembled from many sources with much diligent work by James Britell of NHTSA's Office of Crash Avoidance. Funding came from: the National Highway Traffic Safety Administration; Federal Highway Administration; U. S. Army Tank Automotive Command; American Automobile Manufacturers Association; Rubber Manufacturers Association; National Research Council of Canada; and International Brotherhood of Teamsters. Good advice and wise council came from the members of the SAE Truck Tire Characteristics Task Force. Among those who contributed in an

especially significant way were Charles Powell (Navistar International Transportation Corp.), Fred Wheeler (Michelin Technical Services, Inc.), and Claude Brunot (Goodyear Tire and Rubber Co.). Finally, we would be remiss if we didn't mention Gary Pollak of SAE Cooperative Research who insured that all the paperwork got done and that the I's were dotted and the T's crossed.

NOMENCLATURE

α	=	Slip Angle
F_x	=	Longitudinal Force
F_y	=	Lateral Force
F_z	=	Normal Force
γ	=	Inclination Angle
M_x	=	Overturning Moment
M_z	=	Aligning Moment
P	=	Inflation Pressure
R_l	=	Loaded Radius
s	=	Nondimensional Slip
S	=	Test Speed
SR	=	Slip Ratio
T_s	=	Spindle Torque

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