



400 COMMONWEALTH DRIVE, WARRENDALE, PA 15096-0001 U.S.A.

Truck Tire Characterization



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Free-Rolling Cornering Test Heavy Duty Truck Tire



M. G. Pottinger,¹ W. Pelz,² G. A. Tapia,³ and C. B. Winkler⁴

A Free-Rolling Cornering Test for Heavy Duty Truck Tires⁵

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ABSTRACT: Under the auspices of the SAE Truck Tire Characteristics Task Force, the background to support the creation of a *recommended practice* for experimentally determining the free-rolling cornering properties of heavy duty truck tires has been developed. The value of such a *recommended practice* lies in the establishment of a broadly accepted procedure for obtaining the free-rolling cornering data needed to represent tires in vehicle dynamics simulations of commercial trucks.

This paper lays the proposed test procedure and background data before the technical community. The paper contains: a summary of the proposed test procedure; example data from CALSPAN and UMTRI taken using the proposed procedure; a statistical comparison of the data from CALSPAN and UMTRI; a discussion of the effect of inflation pressure on the data; a discussion of how the proposed test affects tire cornering properties and tread surface topography; and a look at the projected future work of the task force.

KEY WORDS: truck tires, force and moment, free-rolling cornering, lateral force, aligning moment, test machine correlation, testing

The purpose of the work reviewed in this paper is to establish a standardized testing procedure for producing free-rolling tire force and moment data for use in vehicle dynamics Simulations employed in the design and development of heavy duty trucks.⁶ This 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]⁷. The test procedures which are developed are to be expressed as SAE Recommended Practices (J-Documents).

This study was conducted as an 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 manufacturers, government, and testing organizations who all have an interest in improving the ability of the engineering community to perform analytical design in

¹ Smithers Scientific Services, Inc., 1150 N. Freedom St., Ravenna, OH 44266.

² Dept. of Mathematical Sciences, The University of Akron, Akron, OH 44325-4002.

³ CALSPAN Corporation, P. O. Box 400, 4455 Genessee St., Buffalo, NY 14225.

⁴ UMTRI, The University of Michigan Transportation Research Institute, 2901 Baxter Rd., Ann Arbor, MI 48109-2105.

⁵ Presented at the fourteenth annual meeting of the Tire Society at the University of Akron, Akron, Ohio, March 21-22, 1995.

⁶ 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.

⁷ Numbers in brackets refer to references listed later in this paper.

support of good handling. Many members of this group helped with the work reported and are recognized in the Acknowledgments.

The work of this project began with the synthesis of a test procedure of each type which had a good chance of meeting the program goals. Then experimental evaluations for each procedure were designed. From these parts the Statement of Work [1]⁸, which has guided Phase 1 Part 1 of this project, was assembled. Although development of three procedures is intended, this paper deals with only one, the Free-Rolling Cornering Test.

The task force chose to examine the comparative capabilities of the two public-domain organizations with equipment able to test heavy duty truck tires, CALSPAN and 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 perform wet testing. It 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) which is 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 test station located on the centerline 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 accomplished at this test station. The wheels on the test axle run outboard of the nominal eight foot width of the vehicle. 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. Rather the left tire serves only as a counter acting 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 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.

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.

⁸

The Statement of Work and reports by Smithers Scientific Services, Inc. are available from SAE Cooperative Research, SAE International, 400 Commonwealth Dr., Warrendale, PA 15096-0001.

The body of this paper begins with a discussion of the full test procedure developed in the project and applied by CALSPAN and UMTRI. This discussion also includes some modifications to the procedure which will be included in the suggestions for the recommended practice. 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.

The Test Procedure

The test procedure has not yet been put into the formal arrangement seen in a recommended practice. Instead this section gathers together those elements which will be formally assembled.

Test Condition Limitations

There are three significant limitations which must be observed in order to produce good data:

1. The tires to be tested must have been stored under either equivalent or well understood conditions.
2. Tires must be tested within a carefully controlled ambient temperature range.
3. The test surface must be of a consistent character.

Tire storage under equivalent or well understood conditions is necessary to prevent invalid modeling comparisons. Pottinger and Marshall [2] showed that tire force and moment properties change significantly over time, as tires age. The rate of change in aging shows a power law dependence on storage temperature. Thus, comparative force and moment test results obtained from tires of either drastically different ages or from tires which have been stored at very different temperatures may be quite misleading. There is no way to make a precise stipulation as to storage practice, but it is very desirable that tires intended for force and moment testing be stored at a temperature below 75°F (24°C).

Ambient Temperature during testing influences tire force and moment properties, Pottinger et al [3]. This is strictly controllable. However, the practical problems of productivity in over-the-road force and moment testing as practiced using the UMTRI Mobile Tire Tester require that the allowable test temperature range not be too limited. An allowable range of 60°F to 80°F (16°C to 27°C) was chosen limiting the expected lateral force (F_y)⁹ error to $\pm 2\%$.

Test surface consistency is crucial to good results. The dry test surfaces used by CALSPAN and UMTRI are quite different. 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

⁹

Whenever a technical term is introduced, both the term and any related symbol appear in the text. The terms and symbols also appear grouped in the nomenclature appendix. All terms are defined in SAE J670e [6].

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

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. Fortunately, this didn't perturb the free-rolling cornering test, but caused many instructive friction related problems in the straight-line braking test [4].

UMTRI used the Dana Corporation track at Ottawa Lakes, Michigan.

A very significant surface effect showed in the UMTRI and CALSPAN data. This was easily seen in the longitudinal force (F_x) data from the straight line braking test [5]. Figure 3 illustrates what can happen as nondimensional slip (s) increases. Fortunately in the crucial s -range for free-rolling cornering a linear relationship is a reasonable approximation to reality. Divergence from linearity has just become significant when the absolute value of s is 0.10. This value corresponds to a slip angle (α) of about 6° . Equations (1) and (2) show the relationship of s to α and slip ratio (SR).

$$s = \sin(\alpha), \text{ For Free-Rolling Cornering} \quad (1)$$

$$s = SR, \text{ For Straight-Line Braking} \quad (2)$$

The longitudinal force (F_x) data we have just been discussing were introduced to make the point that surface properties are pre-eminently important in the measurement of tire forces and moments and must be well controlled. If two test sites had exactly identical test machines and used precisely identical tires, test procedures, and analyses, but tested on non-identical surfaces, the test results can be expected to be different. Fortunately, at low slip angles on dry surfaces these differences aren't too important. Elsewhere these differences may be crucial. Therefore, surface controls are needed.

The surface data just mentioned will be revisited in great detail in a later paper.

Inflation Pressure

Tire properties are strong functions of inflation pressure. Therefore, it is very important to choose an inflation pressure representative of actual tire service rather than an arbitrary pressure. Further, different tire designs may heat differently in operation which would yield different operating pressures even though the tires begin operation at the same cold inflation pressure. Thus, a small pretest is used to determine the pressure to which the tire will be regulated in the regular test. The length of the pretest is based on experience with heavy duty tires and aims at producing a thermal state approximately representative of equilibrium operation. The procedure is as follows:

1. Mount the experimental tire on the test rim specified by the appropriate tire and rim standards organization.¹⁰
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 in the test tire (P).¹¹ P is the inflation pressure that will be used during tire conditioning and test.

Pre-Test Conditioning

In addition to surface friction and tire age plus storage history, already discussed, 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. Therefore, the pre-test conditioning is aimed at assuring thermal equilibration of the test tire as well as a modest consistent exercise of a new tire prior to actual testing.¹² The purpose is to simulate an initial test condition for a new tire which is apt to exist a few hours after highway usage starts.

The 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 force and moment measurement 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.¹³
5. Maintain γ = 0.0 degrees.

¹⁰ An example of a tire and rim standards organization is the Tire and Rim Association.

¹¹ Carrying out this procedure at both CALSPAN and UMTRI lead to the same answer.

¹² The exact correct exercise state is unknown, but not likely to be very severe. [2]

¹³ S = 45 mph (72 km/hr) in the work reported in this paper. This speed was chosen to accommodate the acceleration characteristics of the UMTRI Mobile Tire Tester. Choice of a higher S would have resulted in protracted testing.

Table 1 - Pre-Conditioning Operating Conditions

Step	Distance miles (km)	α degrees
#1	S X 1 hour	0.0
#2	0.5	1.0
#3	0.5	-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 , do the α sequence in order, set the second F_z , do the α sequence in order, and so forth until the α sequence has been completed for all Normal Forces.

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. $\alpha = 0.0, 1.0, -1.0, -2.0, 2.0, 4.0, -4.0, -6.0, 6.0$ degrees.
6. After each α or F_z is complete the tire shall make two complete revolutions prior to the start of data acquisition to allow force and moment equilibration. Data acquisition shall be over at least two, but not more than 10, tire revolutions to give adequate data while limiting within-the-test tire wear.

Data Acquisition and Reporting

The data acquisition specifications are specific to the free-rolling cornering test. In brief outline, the free-rolling data are to be acquired and reported as follows:

1. The data to acquire are F_x , F_y , F_z , M_x , M_z , R_1 , α , and γ .
2. All data are to be reported using the SAE J670e Tire Axis System [6].
3. Each reported data point is to be the average of the data taken over at least two revolutions of the tire so as to suppress tire uniformity effects. It is suggested that at least 32 points spaced equally around the tire circumference comprise the data for each tire revolution.
4. The transducer interaction and uniformity corrected data shall be transmitted as ASCII files.¹⁴ Graphical examples of the form of the reduced data appear in the results section of this paper.

General Comments on Control Tire Procedures

Earlier in the discussion of *Test Condition Limitations* explicit notice was taken of the importance of test surface consistency. At least as important is the assurance that a test machine exhibits consistent calibration with respect to gains and zeroes of the angle and force measuring sensors. During the course of this project [1], problems of both types were encountered. In hindsight, it would clearly have been useful to include control tire procedures for monitoring both surface condition and machine calibration as part of the initial test procedure. Control tire procedures will be introduced in Phase 1 Part 2 of the project. [7] They are briefly discussed here.

Test surface consistency may be lost in two ways: gradually due to wear or weathering, Whitehurst [8], or precipitously when worn surfaces are replaced. As noted earlier, surface changes were not a significant problem for the free-rolling cornering data produced by the test proposed in this paper as the slip involved is small. Therefore, discussion of the test surface consistency control procedure will be deferred until later papers on straight-line braking and combined cornering and barking.

Consistent calibration can be lost through equipment drift, equipment damage, or through miscalibration. Undetected miscalibration at one site became a problem in the free-rolling cornering portion of this project. The following control procedure addresses this issue.

Control Procedure for Slip Angle Gain and Zero

Control Tire Selection and Handling

Control tires should be chosen to be of approximately the same diameter as the test tires and allow use of the same measuring transducer as will be used for the test tires so that no machine changes are necessary between control tire tests and the actual free-rolling cornering tests. By way of example, for the part of the Truck Tire Characteristics program being reported, it would have been logical to use 295/75R22.5 control tires.

¹⁴

The recommended practice will contain specific file format requirements and data reduction requirements.

Each control tire should be branded with an unique serial number on the side of the tire which will be mounted outward during testing.

All control tires should come from the same batch and should be stored out of the sun at a temperature of 75°F (24°C) or less to retard changes due to aging [2]. Control tires should be replaced whenever they have worn down in tread depth by approximately 0.120 inches (3 mm).¹⁵

Control tires prepared to study gain are not to be used to monitor surface friction because the surface friction control procedure will rapidly change the low slip angle properties of the slip angle gain and zero control tires..

Control Tire Baseline Test

Each control tire is to be individually pre-tested as described below to provide baseline data.¹⁶

The baseline test surface, if indoors, should be freshly applied and have had both a single free-rolling cornering test as defined in this paper, and a single straight line braking test as defined in Reference 1 run on it prior to control tire pre-testing. The surface break-in should use a sacrificial surface break-in tire. The test surface, if outdoors, should be clean, dry, and free of surface contamination.

All testing shall occur on the standard sized rim for typical application of the control tire.

The tire shall be mounted on the test machine so that all testing will occur with the normally outward side of the tire rotating clockwise when viewed by an observer.

Inflation pressure during both conditioning and the baseline test is to be regulated to the maximum rated inflation for the control tire specification used.¹⁷

Prior to baseline testing each tire should be conditioned for 5.0 minutes at a speed of 10 mph (16 km/hr) at its maximum rated load. During this conditioning, Inclination and Slip Angle should both be zero.

Immediately following conditioning, the candidate control tire is to be tested according to the following test procedure.

¹⁵ Since tire force and moment properties are dependent on tread depth, it would be desirable to allow as little tread depth reduction as possible. However, a practical compromise of ideal behavior and cost is necessary. This means that the analysis must account for the resulting changes in tire behavior as is noted later.

¹⁶ It would be ideal to establish control tires at one facility and then use them at another facility. In this way potential initial calibration errors prior to any testing could be detected. However, when this is not feasible, pre-testing should occur immediately after calibration at the using facility.

¹⁷ The control procedure is intended to be a quick, low wear, procedure so it differs from the general free-rolling procedure in numerous points.

1. Maintain $\gamma = 0.0$ degrees.
2. Maintain a test speed of 10 mph (16 km/hr).
3. Maintain $F_z = -100$ percent of the maximum rated load.
4. Repeat the following slip angle sequence four (4) times. $\alpha = 0.0, 0.5, 1.0, -0.5, -1.0$ degrees. This will produce four separate sets of test data.

Baseline Data Analysis

As the first step of this analysis, all $F_y(\alpha)$ and $M_z(\alpha)$ data should be corrected for any F_z errors according to the following equations:¹⁸

$$F_{Y@Rated} = (F_{Z@Rated}/F_{ZMeasured}) * F_{YMeasured} \quad (3)$$

$$M_{Z@Rated} = (F_{Z@Rated}/F_{ZMeasured}) * M_{ZMeasured} \quad (4)$$

Next, aligning stiffness, cornering stiffness, $F_y(\alpha=0^\circ)$, and $M_z(\alpha=0^\circ)$ are to be determined from each of the four sets of data respectively by use of linear regression. Using these four measurement based values of each parameter, the means and standard deviations (σ) of aligning stiffness, cornering stiffness, $F_y(\alpha=0^\circ)$, and $M_z(\alpha=0^\circ)$ are to be determined. Finally, a separate control chart for each of the four parameters is to be prepared. These charts will be in the form of an x-y plot with the y-axis depicting the value of the parameter and the x-axis depicting time. Each chart is to contain three horizontal lines showing the mean value and the mean value $\pm 2.5\sigma$ values of the parameter charted.¹⁹ These charts will be used to indicate the changes in the zero-values and stiffnesses through the time period of the testing program.

Slip Angle Gain and Zero Control Test

The slip angle gain and zero control test is to be done prior to the first test in a given sequence and then once per day thereafter. The purpose is to alert the tester to potential gain (aligning stiffness and cornering stiffness) or zero shifts ($F_y(\alpha=0^\circ)$, and $M_z(\alpha=0^\circ)$). These shifts may be due to sudden shifts in the behavior of the apparatus or due to an error in a subsequent calibration.

The rim size, inflation pressure, and pre-test conditioning are identical to those used in baseline testing. The test specification, which is as follows, differs from the baseline in that one repetition

¹⁸ Equations 3 and 4 should only be used for correcting small differences between $F_{Z@Rated}$ and $F_{ZMeasured}$.

¹⁹ The aligning and cornering stiffnesses will very slowly increase with time due to tire aging and wear. If a control tire is used for a very long time this effect can become significant. Thus, the mean lines will have a slope with time.

of the angle sequence is used on indoor machines and two repetitions are used on over-the-road testers.²⁰

1. Maintain $\gamma = 0.0$ degrees.
2. Maintain a test speed of 10 mph (16 km/hr).
3. Maintain $F_z = -100$ percent of the maximum rated load.
4. Repeat the following slip angle sequence one (1) time on indoor machines and two (2) times on over-the-road machines. $\alpha = 0.0, 0.5, 1.0, -0.5, -1.0$ degrees.

Analysis of Slip Angle Gain and Zero Control Test Data

The $F_y(\alpha)$ and $M_z(\alpha)$ data, corrected for any F_z error by use of Equations 3 and 4, shall be fit with a straight line and the aligning stiffness, cornering stiffness, $F_y(0)$, and $M_z(0)$ for the control tire obtained. These values shall be plotted on the respective control charts previously prepared during control tire pretesting.

If the values of aligning stiffness, cornering stiffness, $F_y(0)$, and $M_z(0)$ all lie within $\pm 2.5 \sigma$, as determined in the control tire pretesting, start testing. If any of the values lie outside of $\pm 2.5 \sigma$, repeat the gain and zero error test. If any of the values again lie outside of $\pm 2.5 \sigma$, seek the reason that system is no longer operating correctly.

Limitations of the Test Equipment

Both the CALSPAN and UMTRI test machines have mechanical limitations. Those which could impede free-rolling cornering testing 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. These other limitations will be considered in subsequent papers.

CALSPAN

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. In fact 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.

²⁰ The different number of repetitions is a recognition of the relative variance in the results obtained with the two different classes of tire force and moment machines.

6. Slip Angle: None which affect this procedure.
7. Forces: F_x , none affecting this procedure.
 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 capacity of 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*²¹

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.
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 (485 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 , none affecting this procedure.
 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.²²
 M_z , none affecting this procedure.

²¹ Since the UMTRI Mobile Truck Tire Tester 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, the slip angle and normal force controls are open loop. Therefore, significant scatter is to be expected in the data.

²² Results show appreciable variation and an apparent offset as noted later.

Tire Measurement Results

The following sections discuss the results of the free-rolling cornering measurement programs conducted by CALSPAN and UMTRI for this project. The discussion addresses the general functional form and the repeatability of the measurements, the apparent influences of inflation pressure and test-induced changes on force and moment performance, and a statistical analysis and comparison of data from the two facilities.

Functional Form of the Data

For all data, the functional forms are correct except for the M_x data obtained at UMTRI which is shown in Figure 4. These M_x data appear to contain an offset. At this time it would be best not to use M_x data generated on the UMTRI Mobile Tire Tester. The CALSPAN M_x data,²³ shown in Figure 5, conforms better to the normally expected functional form for overturning moment.

Repeatability

For the CALSPAN data, repeatability was excellent for F_y , M_x , M_z , and R_l . Therefore, small samples of well made tires²⁴ are adequate for use with this test procedure when it is applied at CALSPAN. This is verified in the following section on statistical considerations.

Figures 5-8 illustrate the excellent repeatability of the CALSPAN data. In these figures, the data averages appear as lines and the individual tire data from the five (5) tire samples appear as points. In addition, analysis showed that the various pooled standard deviations for the CALSPAN data are small.

For the UMTRI data, as expected (see footnote 21), repeatability was adequate for F_y , M_z , and R_l , but not of the same quality as that seen in the CALSPAN data. Figures 9-11 illustrate the UMTRI F_y , M_z , and R_l repeatability. In these figures, the mean performance is represented as a line with the individual data points being represented as dots. Comparing the observed scatter, it is expected that larger sample sizes will be required between tire specifications at UMTRI to discern differences of a given magnitude than would be required at CALSPAN. See the section on statistical considerations.

Due to the inability of the UMTRI Mobile Truck Tire Tester to control α and F_z precisely (see footnote 21), the UMTRI data cannot be acquired close enough to the target values given in the test description to permit their use without additional analysis. Therefore, enough data should be acquired to allow a surface fit so that information is available where needed. The test proposed in this paper provides sufficient information for that purpose.

²³ The F_z limit for CALSPAN precluded acquiring data at twice rated load as is specified in the test method. Twice rated load appears to allow simulation out to heavy truck rollover.

²⁴ Unfortunately, we do not have criteria for what constitutes well made tires. The tires used in this work are assumed by definition to be: well made and typical of Original Equipment production.

By way of example, the procedure just discussed can be very important. To be able to do the statistical work in this project, the data were surface fitted, then the fits were used to adjust the data point-by-point. Without this procedure, the work on the UMTRI data performed during preparation of this paper would not have been possible.

Pressure Effect

The effect of inflation pressure was examined using CALSPAN data taken with the tire inflation pressure regulated to 110 psig, which is the G-Range maximum rated cold inflation, and then to 125 psig, P (the test inflation pressure) as defined in the test procedure. The resultant behavior is complex. As an illustration, Figure 12 is an attempt to show what happened to Lateral Force. The ratio of F_Y at 125 psig to F_Y at 110 psig at rated load is portrayed in the upper panel. This is a good representation of the effect seen, except at zero slip angle where strong load dependence exists. In all of this, pull force changes with inflation pressure appear to have a large effect. In fact, behavior is sufficiently complex to indicate that simple rules of thumb are insufficient for the description of the influence of inflation pressure on tire force and moment properties. The effects for F_Y , M_X , M_Z , and R_l are not the same. The effect for R_l agrees with the sum of tire mechanics experience. For a detailed discussion of the pressure effects, please see Reference 9.

The Influence of Testing Induced Changes in the Tires on the Tire Force and Moment Data

Testing a tire changes a tire, thus, you can never be completely sure of a tire's properties. In order to bound this "uncertainty"²⁵, in the testing done for this project, the test procedure specified in Reference 1 asked CALSPAN and UMTRI to include a few additional measurements beyond those specified in the Force and Moment Measurement section. At the end of each test run by the method proposed in this paper, without stopping, the testers performed an additional four point test with F_Z corresponding to rated load and $\alpha = \pm 1^\circ, \pm 4^\circ$. Comparison of these final data with the data gathered early in the proposed test data reveals that F_Y and M_Z results are not significantly affected by the free-rolling cornering test. The F_Y and M_Z results are summarized in Figures 13 and 14. M_X (Figure 15) is reduced at higher α . Further, examination of test effects on the basis of average results is valid²⁶. [10]

The resultant wear is slight with no groove having a depth reduction of over 1/32 inch (0.75 mm) due to wear. The tread contour details indicated more severe rounding of the rib edges on the artificial surfaces used at CALSPAN than on Dana's track surface at Ottawa Lakes, Michigan which was used by UMTRI.

Statistical Considerations

As we consider results which follow from statistical examination of the CALSPAN and UMTRI data two very crucial points must be kept in mind.

²⁵ With apologies to Werner Heisenberg.

²⁶ This will be important in assessing the test effect on cornering properties for straight-line braking and combined cornering and braking tests in which the data compared must arise from different tire sets.

1. The tires to be tested must be assumed to be as well made as those used in this paper (See footnote 23.) for the statistical results to be generally correct. This is because the statistical conclusions given here are based on a composite of machine and tire variance. Separating these two variances is not truly possible²⁷.
2. The comparison of results is surface dependent. Thus, the particular results obtained only apply exactly to the surface used at CALSPAN during free-rolling cornering testing and the track surface at Dana's Ottawa Lake, Michigan track which was used by UMTRI. This should not be overlooked when the temptation to mix data from different test sources in a single simulation arises. If the free-rolling test is extended to higher α , as must be done for testing to support modeling of combined cornering and braking [11], the friction properties of the different test surfaces must be carefully considered before mixing data.

Recommended test sample sizes to determine F_y , M_x , and M_z differences between two tire specifications at a stated level of confidence may be determined for test design purposes using Figures 16-18 respectively. For M_x , the variance using the Mobile Truck Tire Tester is large enough that testing to determine M_x would be inadvisable even if the offset noted earlier did not exist.

The required sample sizes are considerably smaller with the CALSPAN machine than with the UMTRI Mobile Truck Tire Tester.

A final analysis method to assure the test engineer of the precise degree of discrimination between specifications actually achieved in the experiment is presented in Reference 12. Unfortunately, the details are too voluminous for presentation in this paper.

Comparison of results between CALSPAN and UMTRI indicates that for the full experimental range, the F_y results were nearly identical (see Figure 19). A careful examination will show differences as slip angle increases (see Figure 20). At $\alpha = \pm 6^\circ$ the CALSPAN TIRF machine yields smaller lateral forces than the UMTRI tester. This reduction at CALSPAN as slip angle increases is probably due to different surface friction at CALSPAN. The $\pm 2\sigma$ band for the CALSPAN results is inside the similar UMTRI band. If cornering stiffness alone is examined (see Figure 21), the CALSPAN machine/surface combination yielded answers statistically identical to the UMTRI machine/Dana surface combination.

M_x measured by the two machines is not comparable as previously noted (see Figure 22).

M_z data measured by the two machines are well correlated, but not the same. There appears to be a gain difference between the two measuring systems (see Figure 23). Possible explanations are: a calibration difference or M_z may be more sensitive than F_y to the difference in surface friction between the test sites.

²⁷ In Phase 1 Part 2 of the project, [7], the test variance will be determined using a reduced free-rolling test applied to a series of 12 test specifications. When this occurs, the general validity of the statistics on which we are now basing the selection of sample sizes will be examined. If it is invalid, adjustments in recommended sample sizing must be made.

R_t results are well correlated, but not the same (see Figure 24). There is again a gain difference between the two machines and perhaps a zero offset, though that is less certain. Calibration differences are a very likely source of the differences between the two machines.

Conclusions

1. The free-rolling cornering test proposed in this paper is usable for its intended purpose.
2. CALSPAN and UMTRI data are both acceptable, however, certain points must be kept in mind to prevent application problems in vehicle modeling.
 - Lateral Force data can be mixed with caution so long as the absolute value of slip angle is less than 6° . If the test were to be extended to higher slip angles, the data obtained in the braking part of this study indicate that mixing data from the two test sites would be inadvisable.²⁸
 - Aligning moment data are correlated, but not identical. They should not be mixed without thought.
3. The statistical tools exist to allow an engineer to choose the number of tires he wishes to test to detect force and moment differences at a given level of confidence using the test proposed in this paper assuming the tire samples used in this study are representative of normal production.
 - The number of test tires required for detecting reasonable differences is not excessive.
4. The test proposed in this paper does not grossly alter the tire's force and moment properties.
5. There is no simple rule of thumb to describe the influence of inflation pressure on force and moment properties of the tires tested.

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

²⁸ There is a real need for research on test surfaces. Indoor machines are quick and precise, but surface problems could sometimes call their results into question as slip becomes large.

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.

Appendix

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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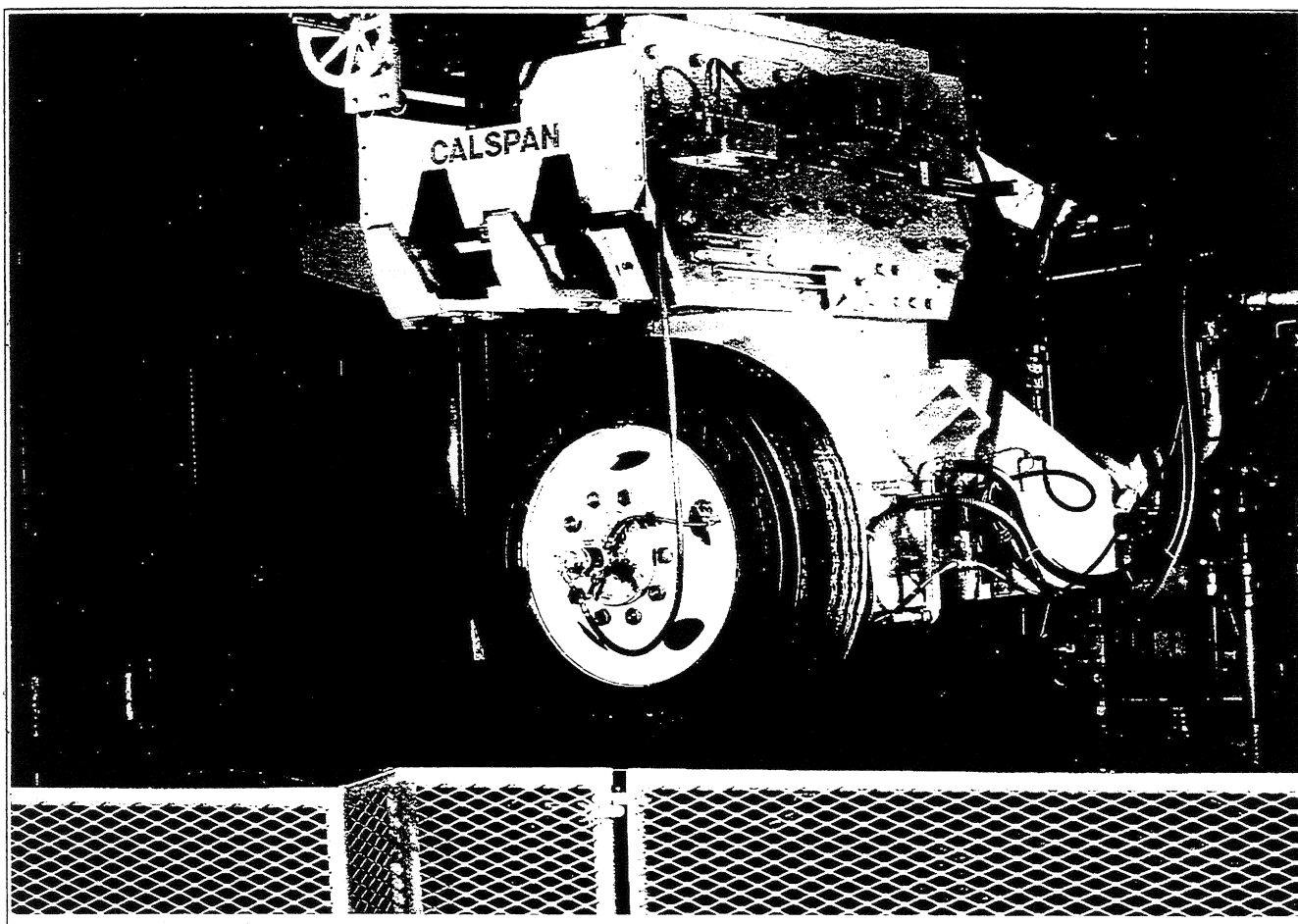


Figure 1 CALSPAN TIRF, Tire Research Facility, Machine

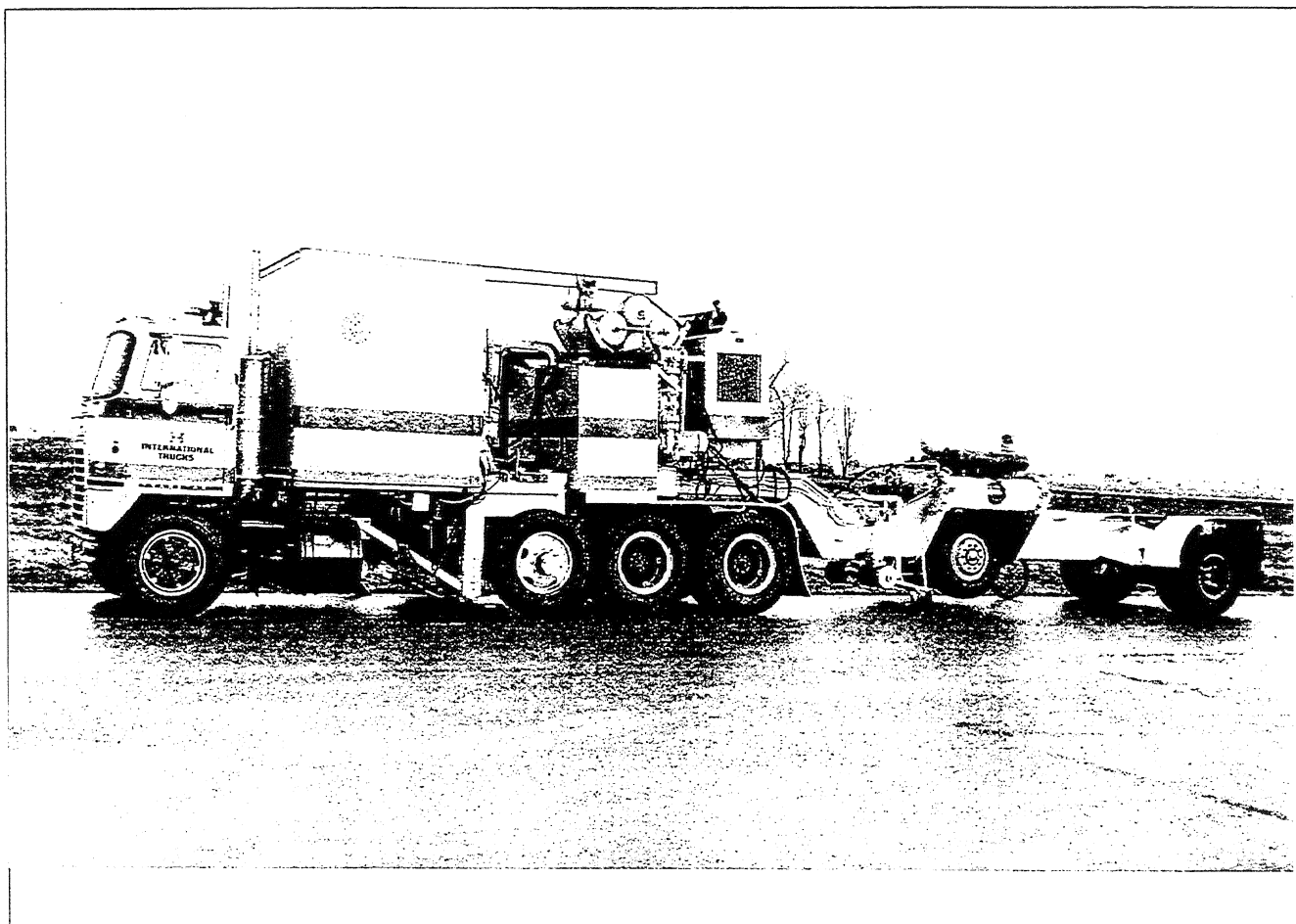


Figure 2 UMTRI Mobile Tire Tester

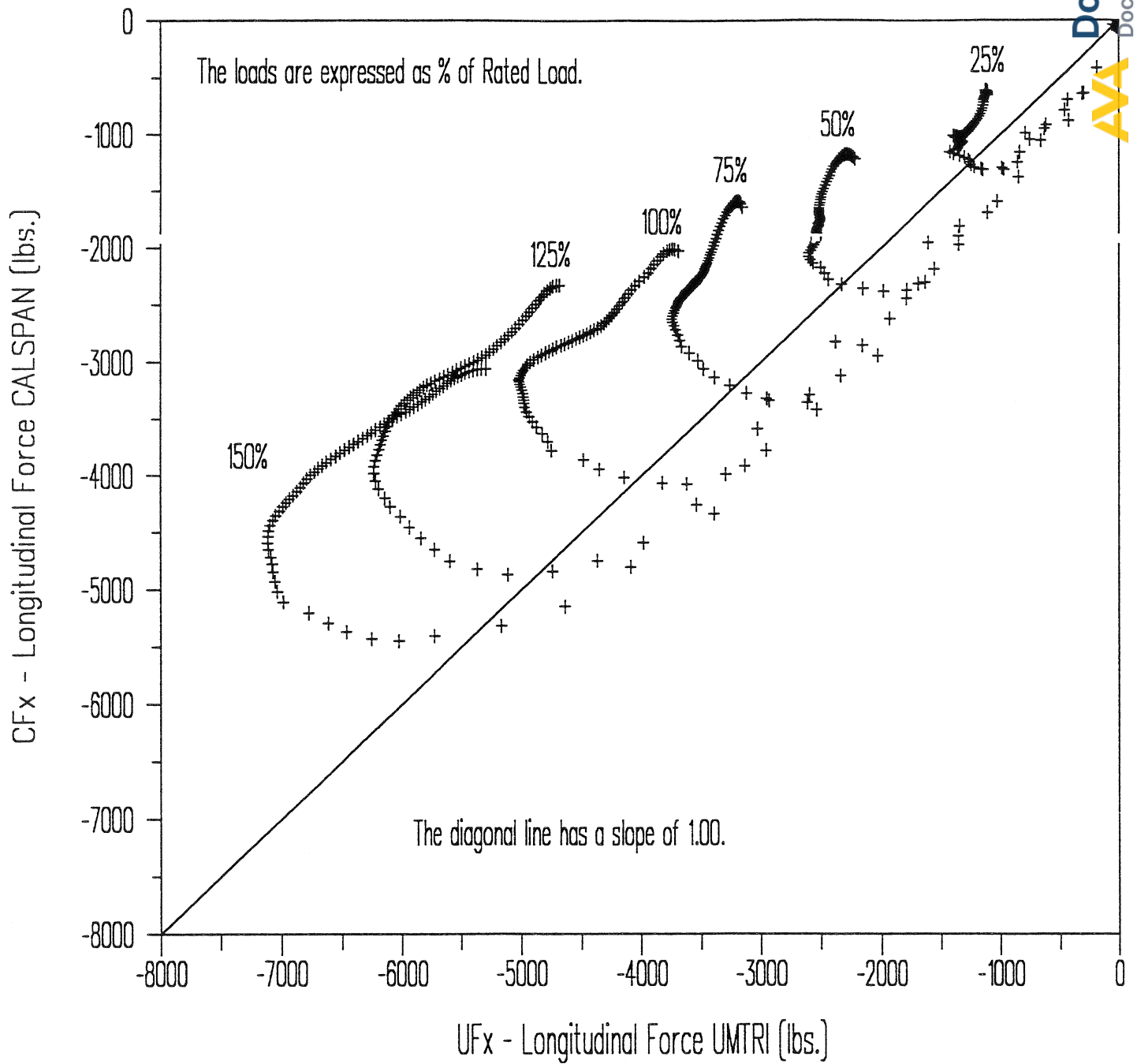


Figure 3 UMTRI Longitudinal Force Data at 125 psig at Dana Proving Grounds vs. CALSPAN Longitudinal Force Data at 125 psig on 120 Grit Polycut®

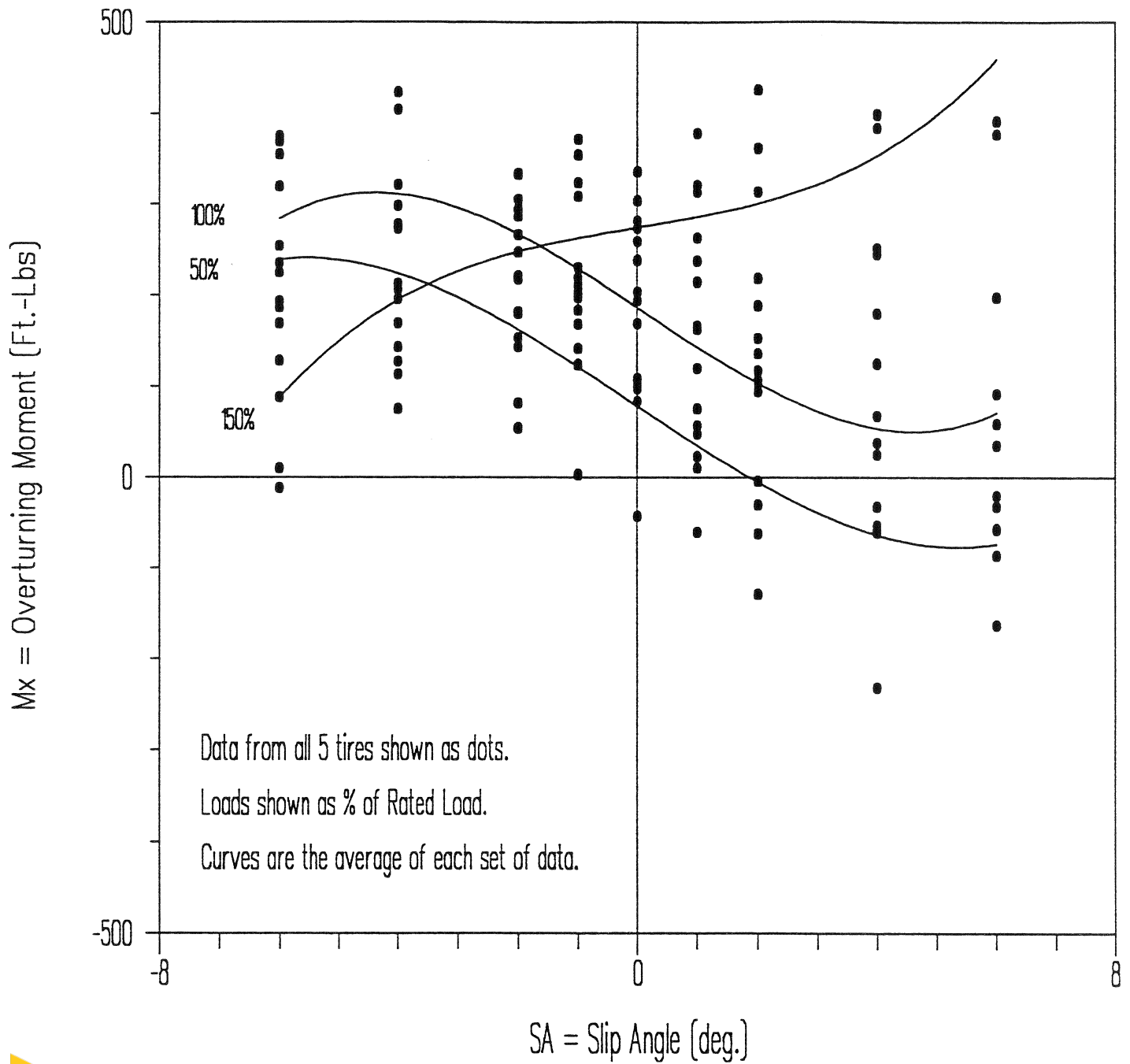


Figure 4 UMTRI Overturning Moment Data at 3 Normal Forces

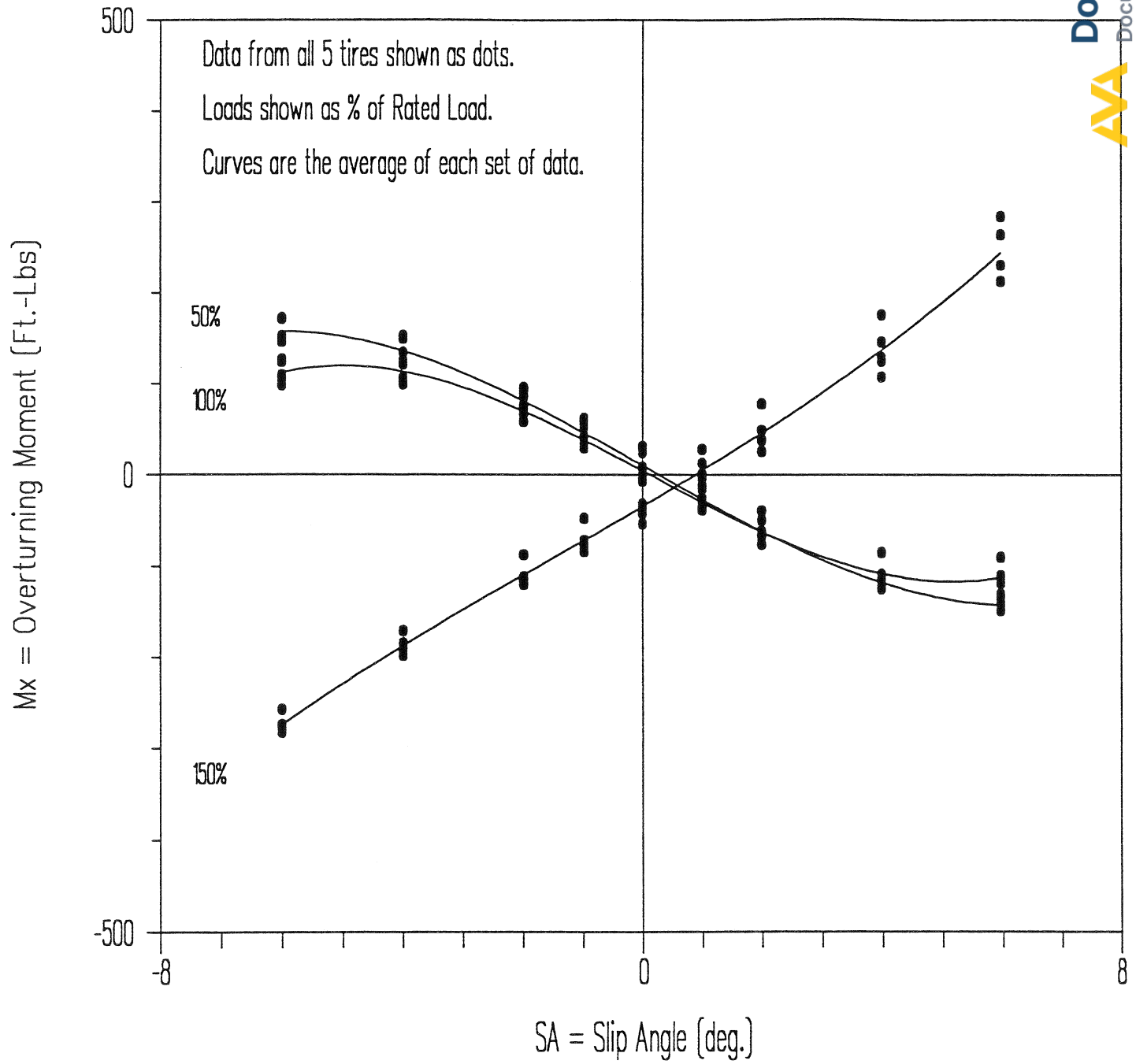


Figure 5 CALSPAN Overturning Moment at 3 Normal Forces

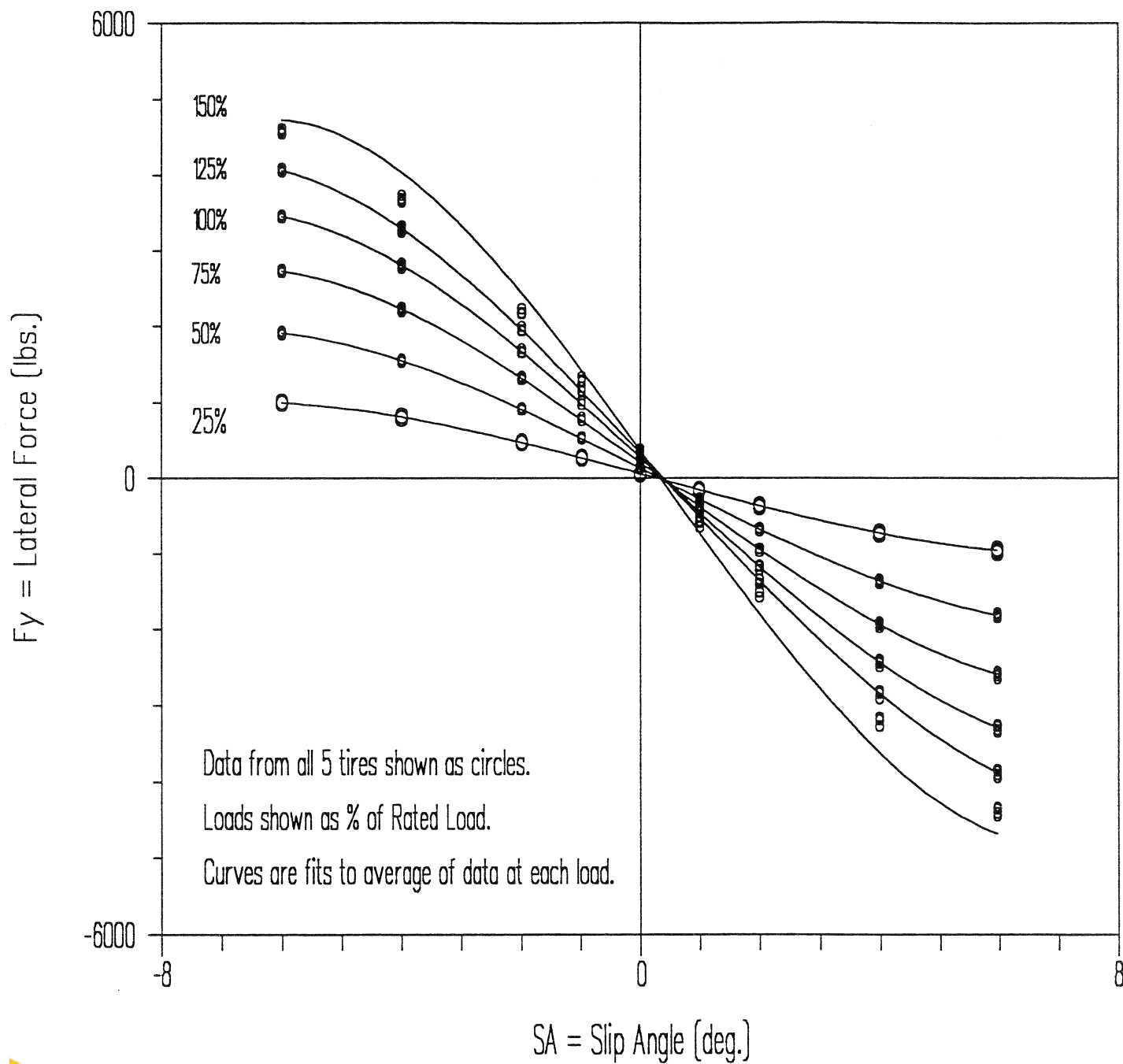


Figure 6 CALSPAN Lateral Force Data at 6 Normal Forces

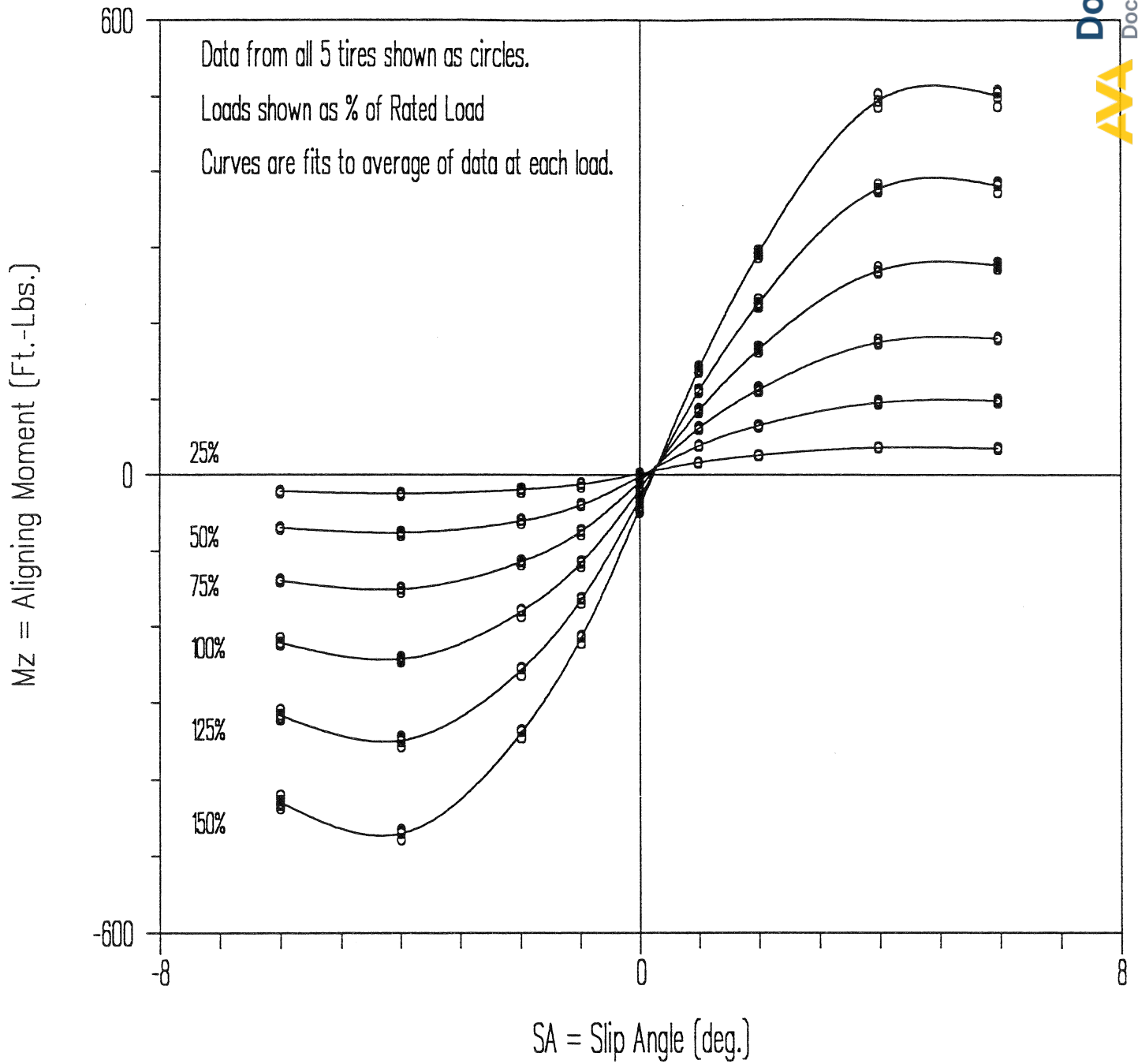


Figure 7 CALSPAN Aligning Moment Data at 6 Normal Forces

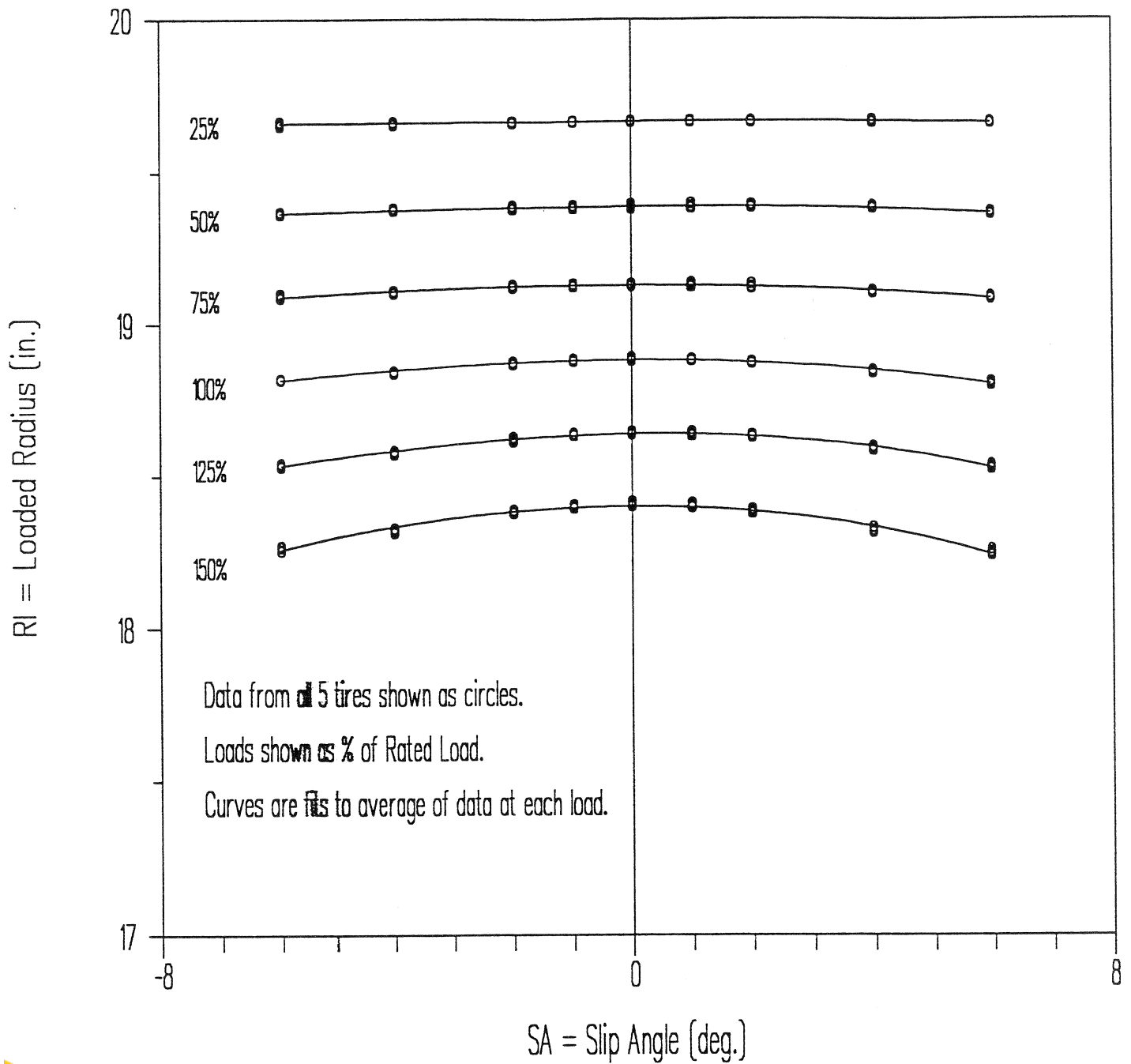


Figure 8 CALSPAN Loaded Radius Data at 6 Normal Forces

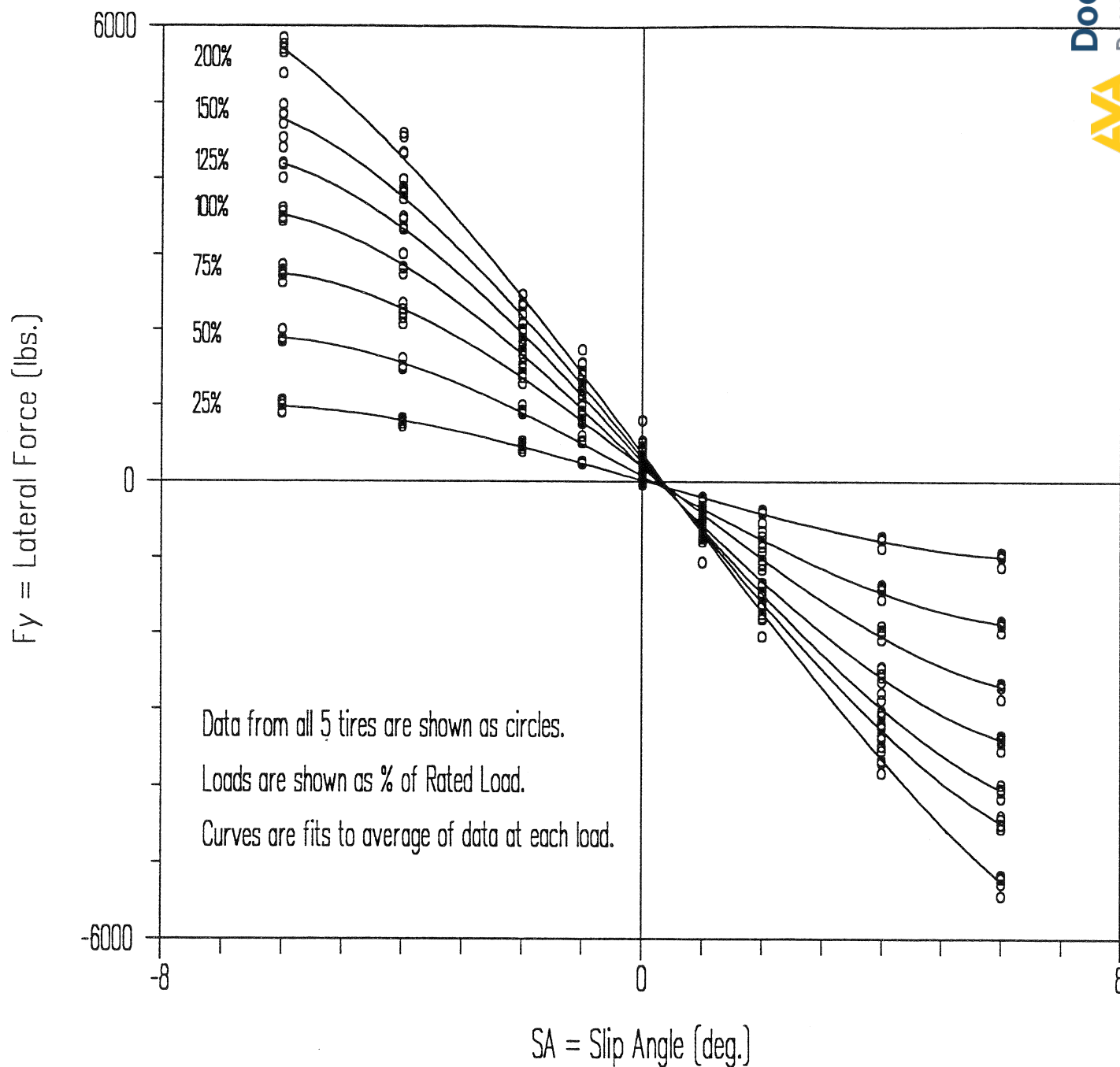


Figure 9 UMTRI Lateral Force Data at 7 Normal Forces

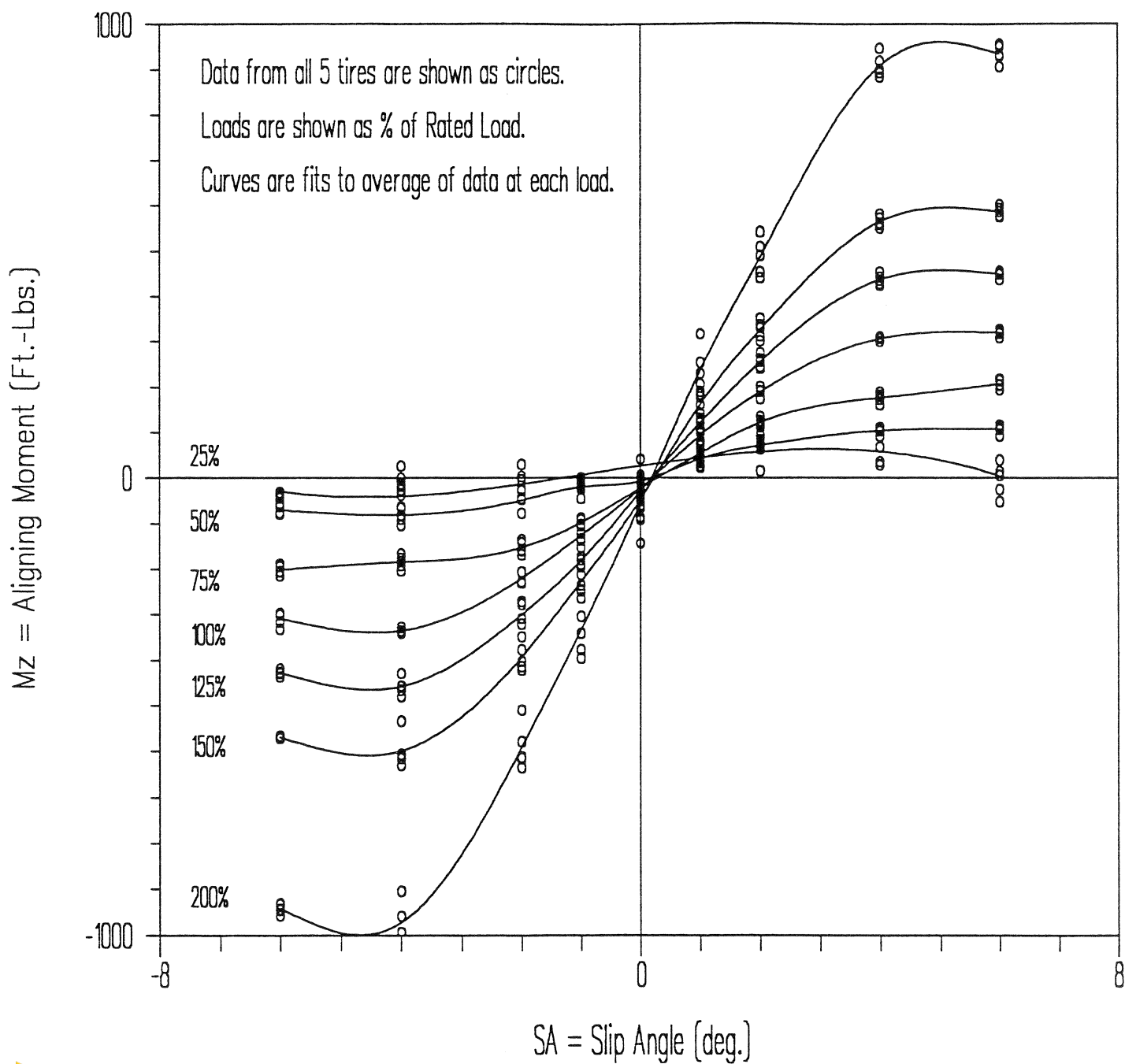


Figure 10 UMTRI Aligning Moment Data at 7 Normal Forces

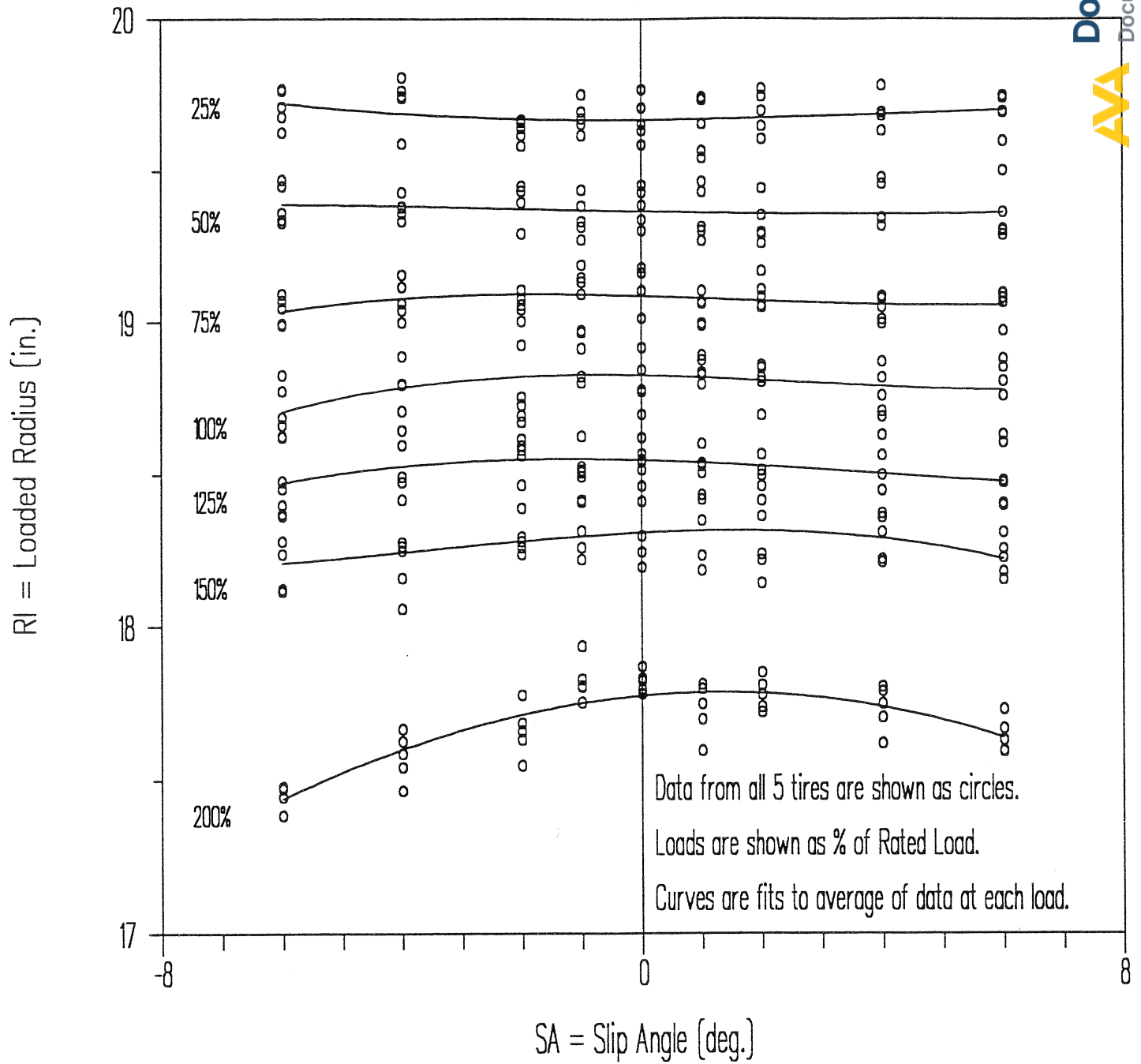


Figure 11 UMTRI Loaded Radius Data at 7 Normal Forces

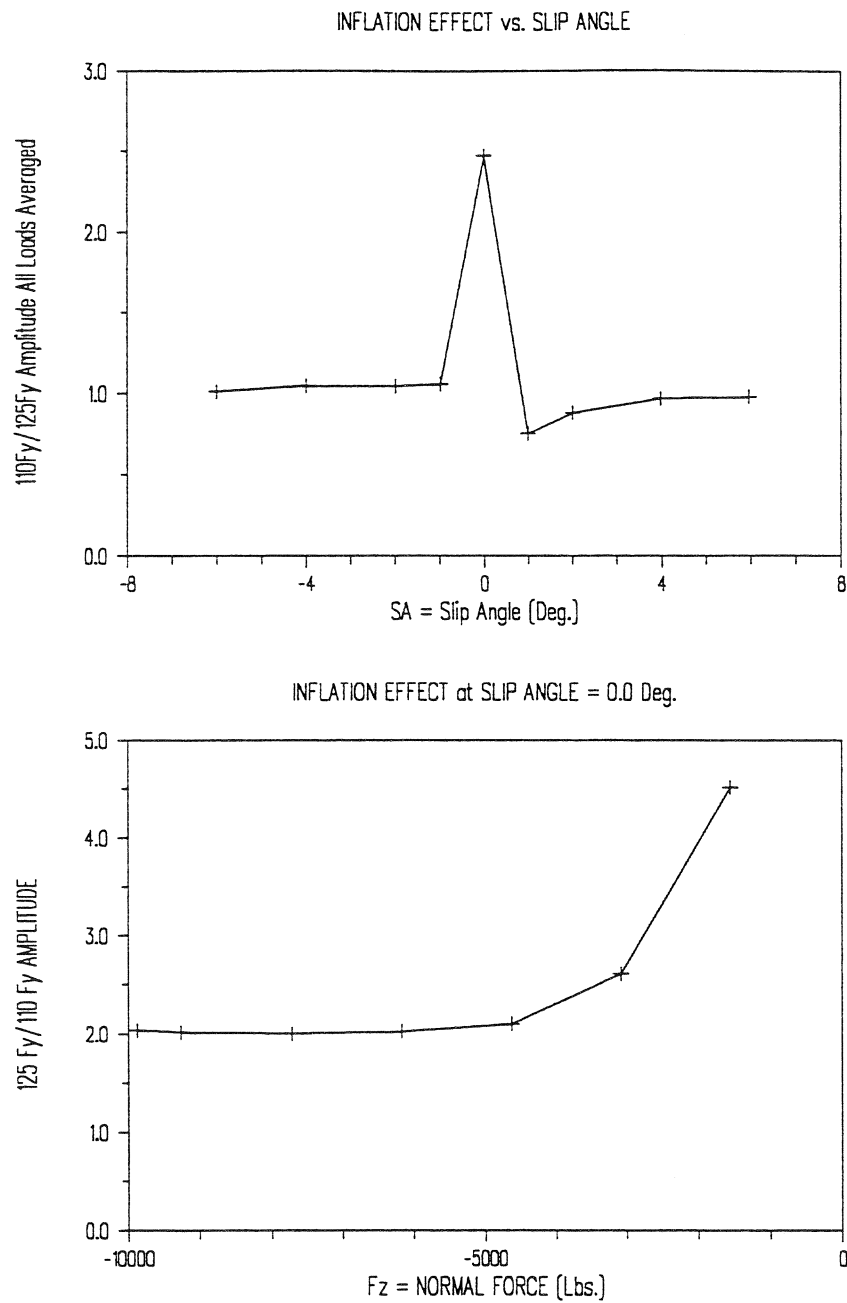


Figure 12 Inflation Pressure Effect on Lateral Force

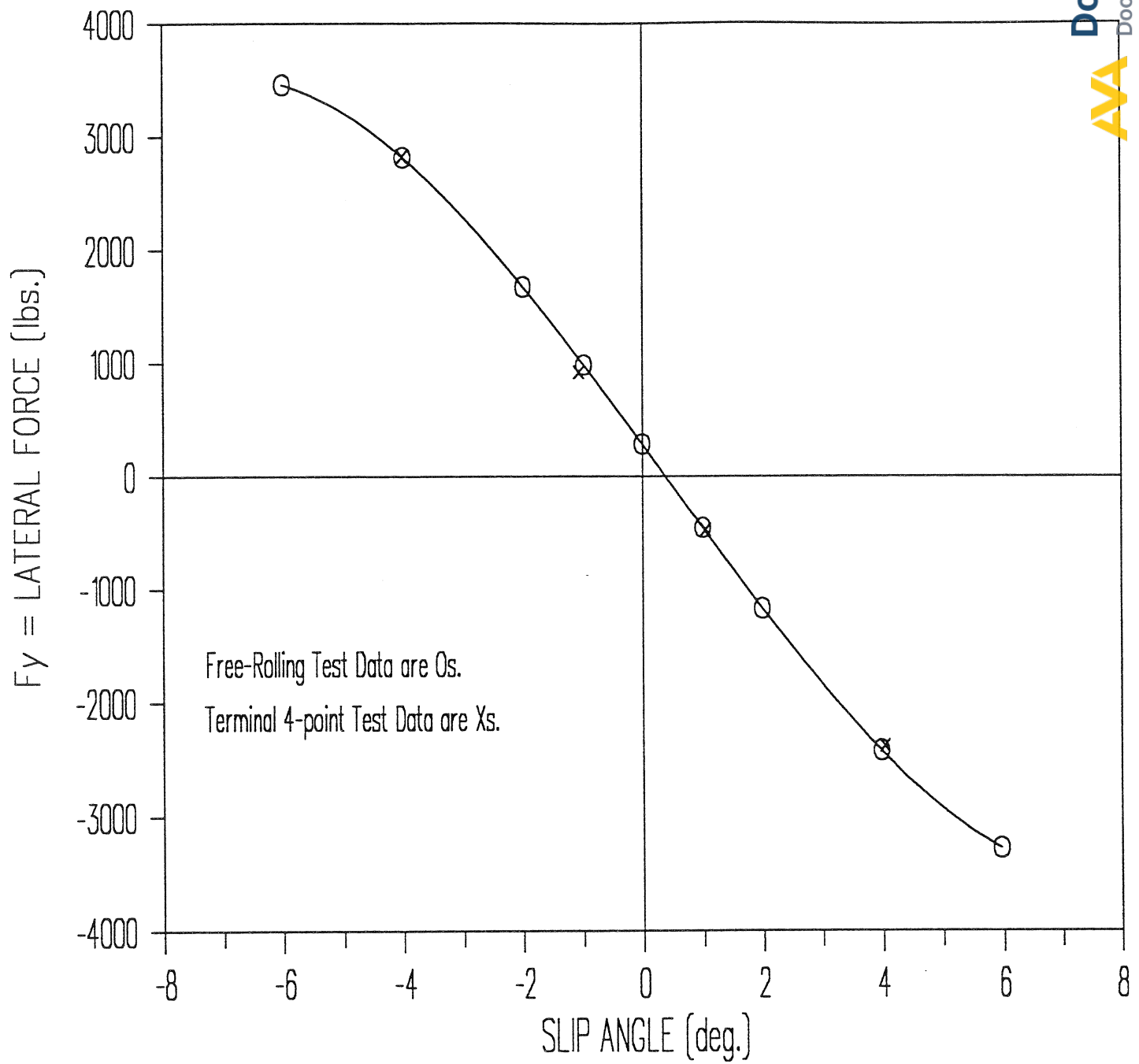


Figure 13 Effect of the Test on Lateral Force using 125 psig CALSPAN Data

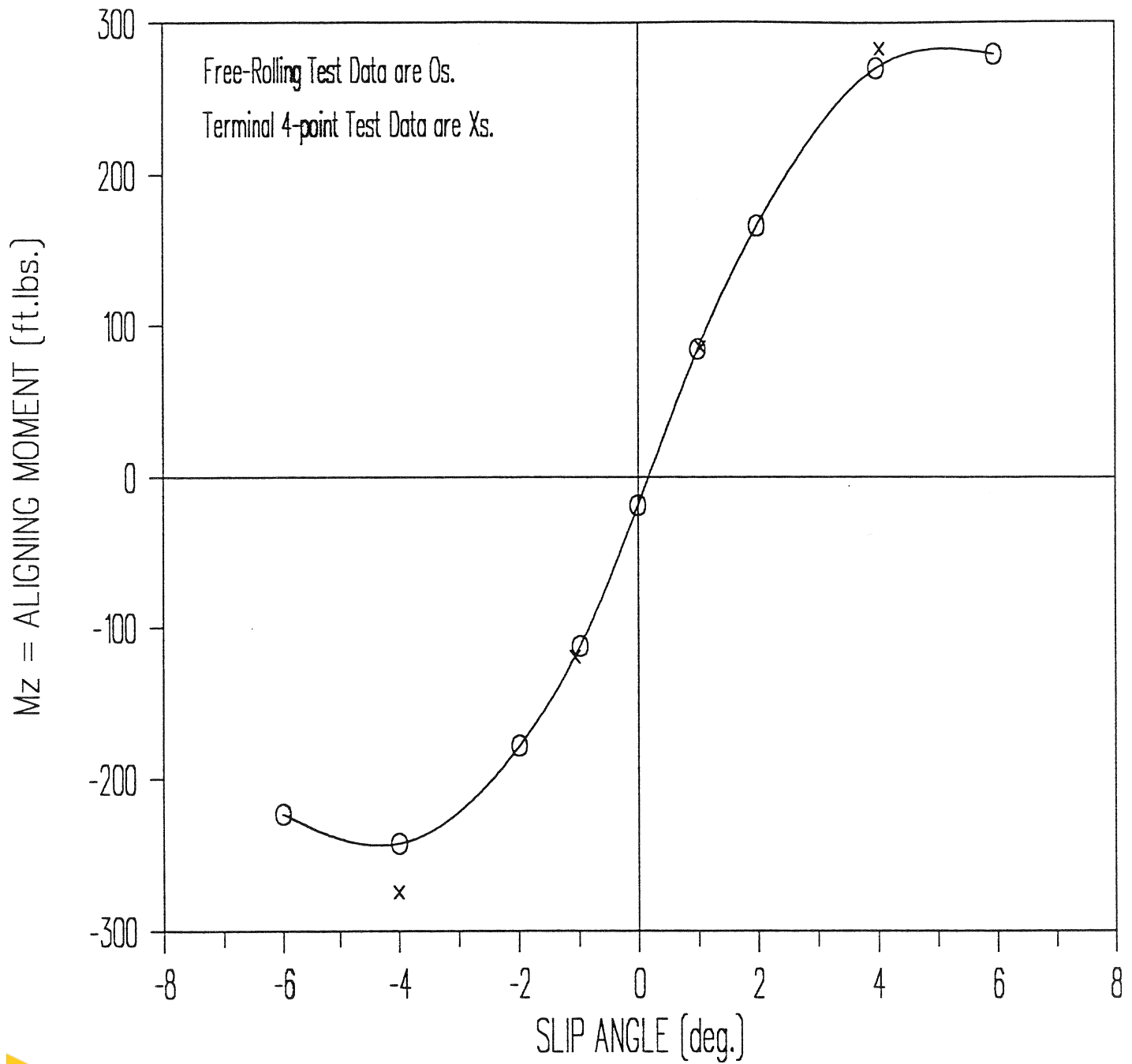


Figure 14 Effect of the Test on Aligning Moment Using 125 psig CALSPAN Data

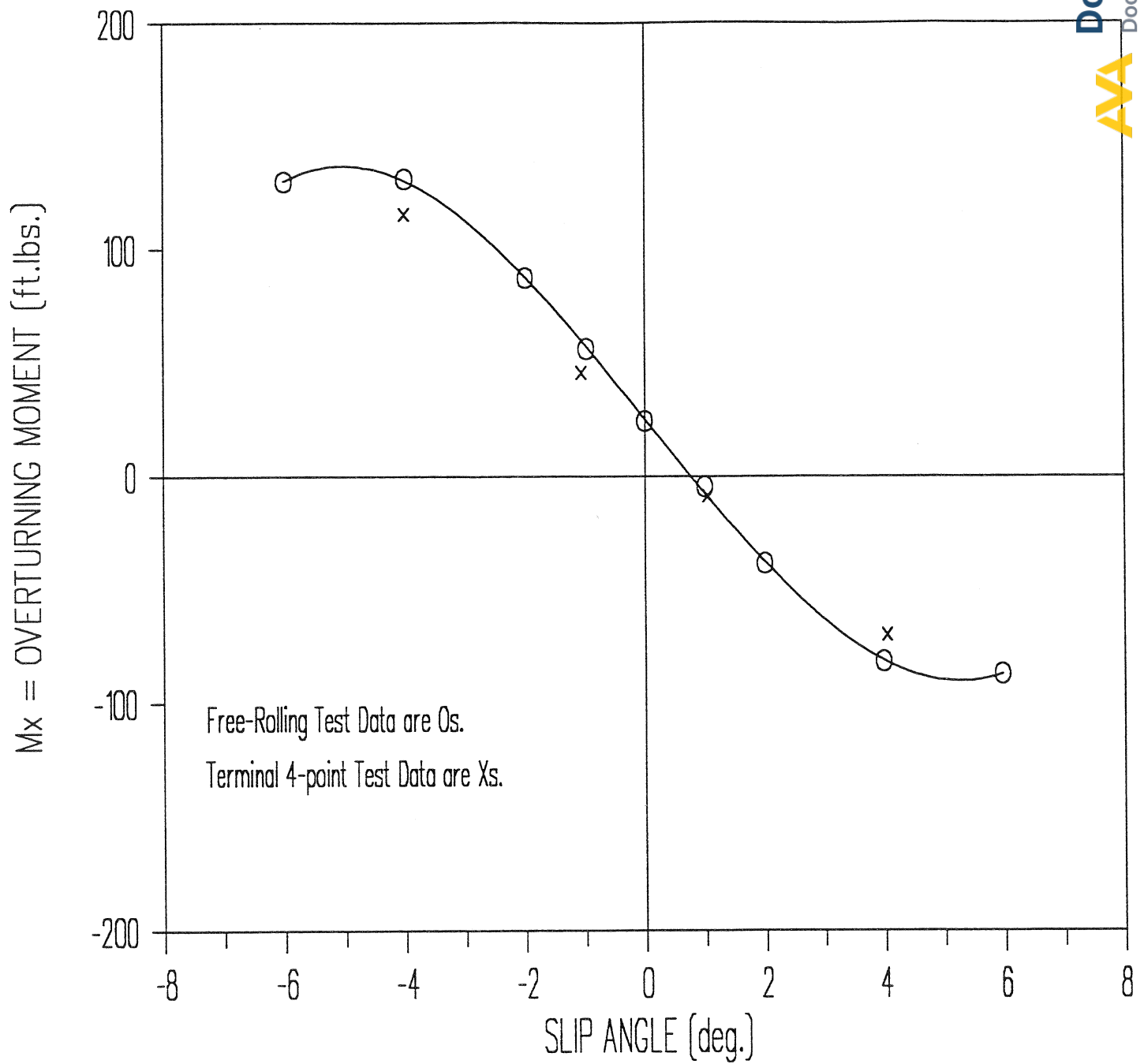


Figure 15 Effect of the Test on Overturning Moment Using 125 psig CALSPAN Data

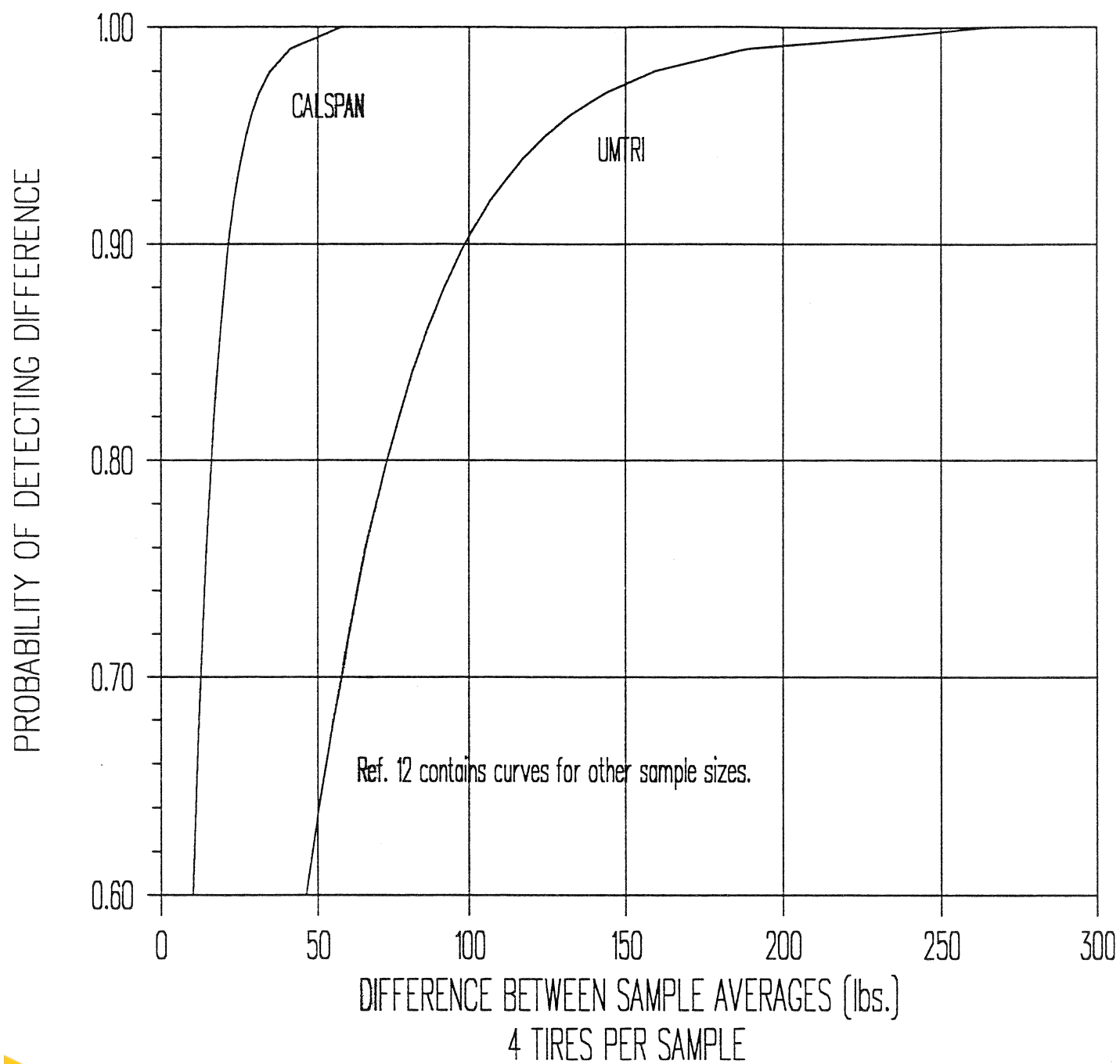
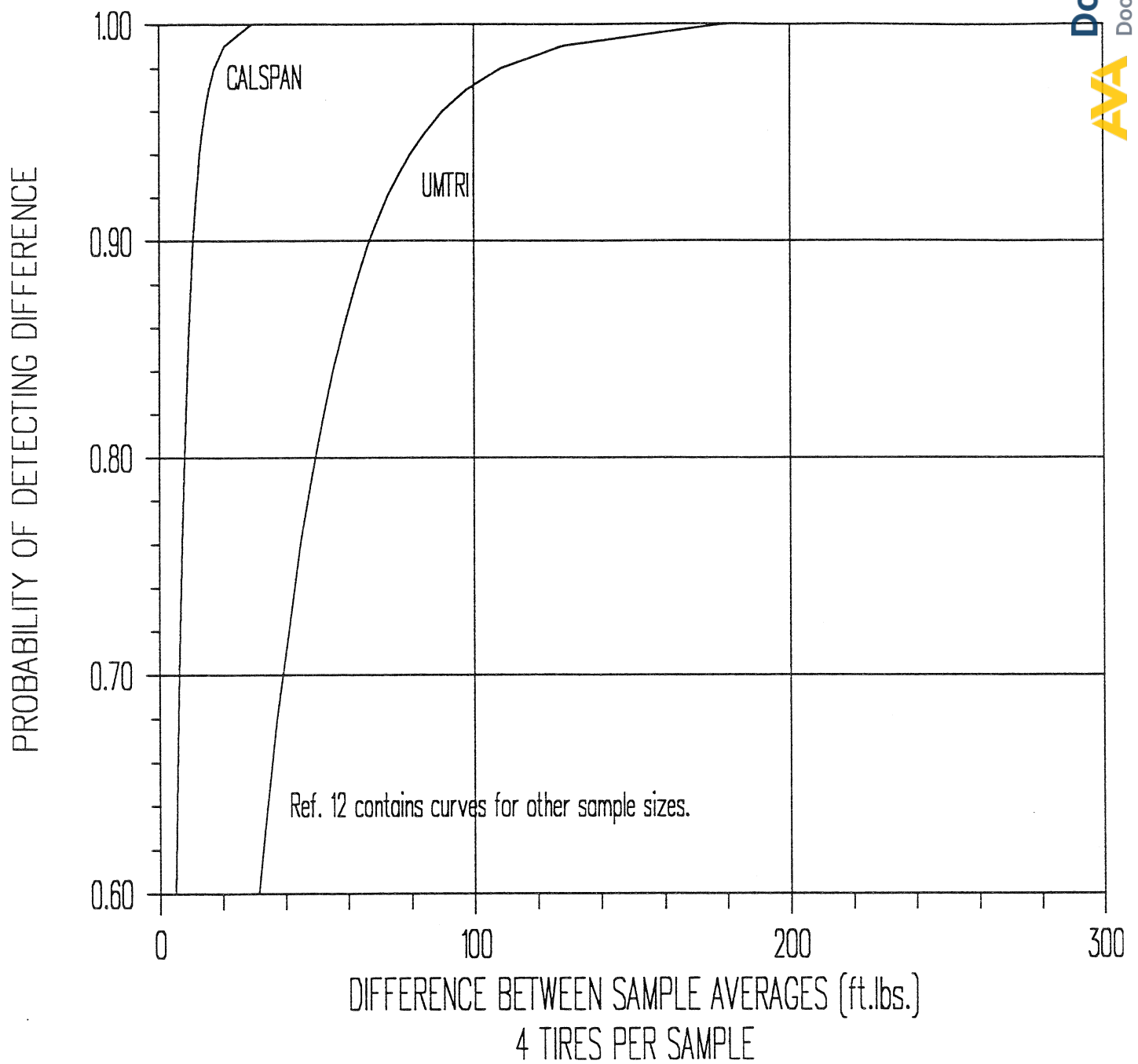


Figure 16 Detectable Differences for Lateral Force

**Figure 17** Detectable Differences for Overturning Moment

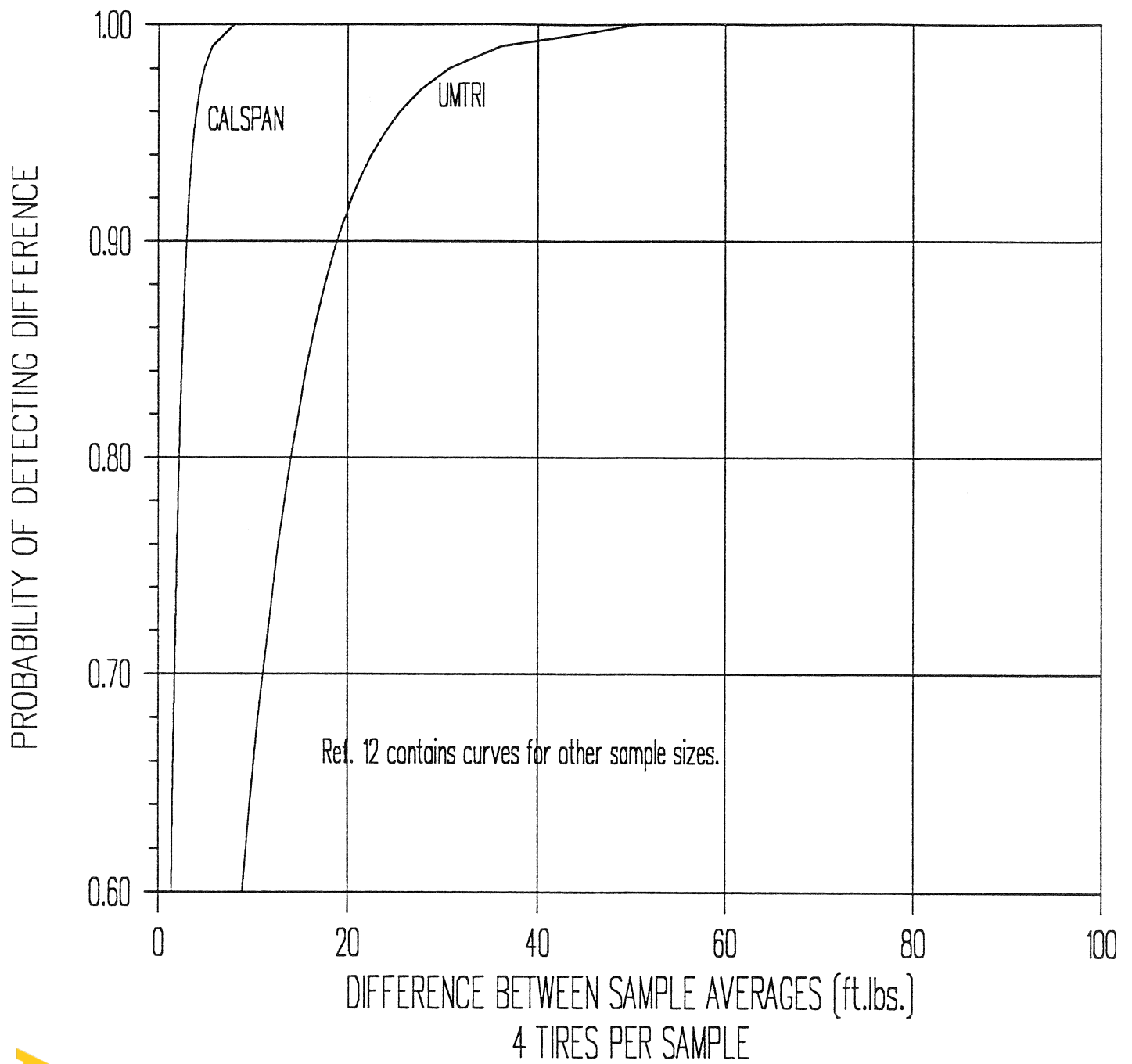
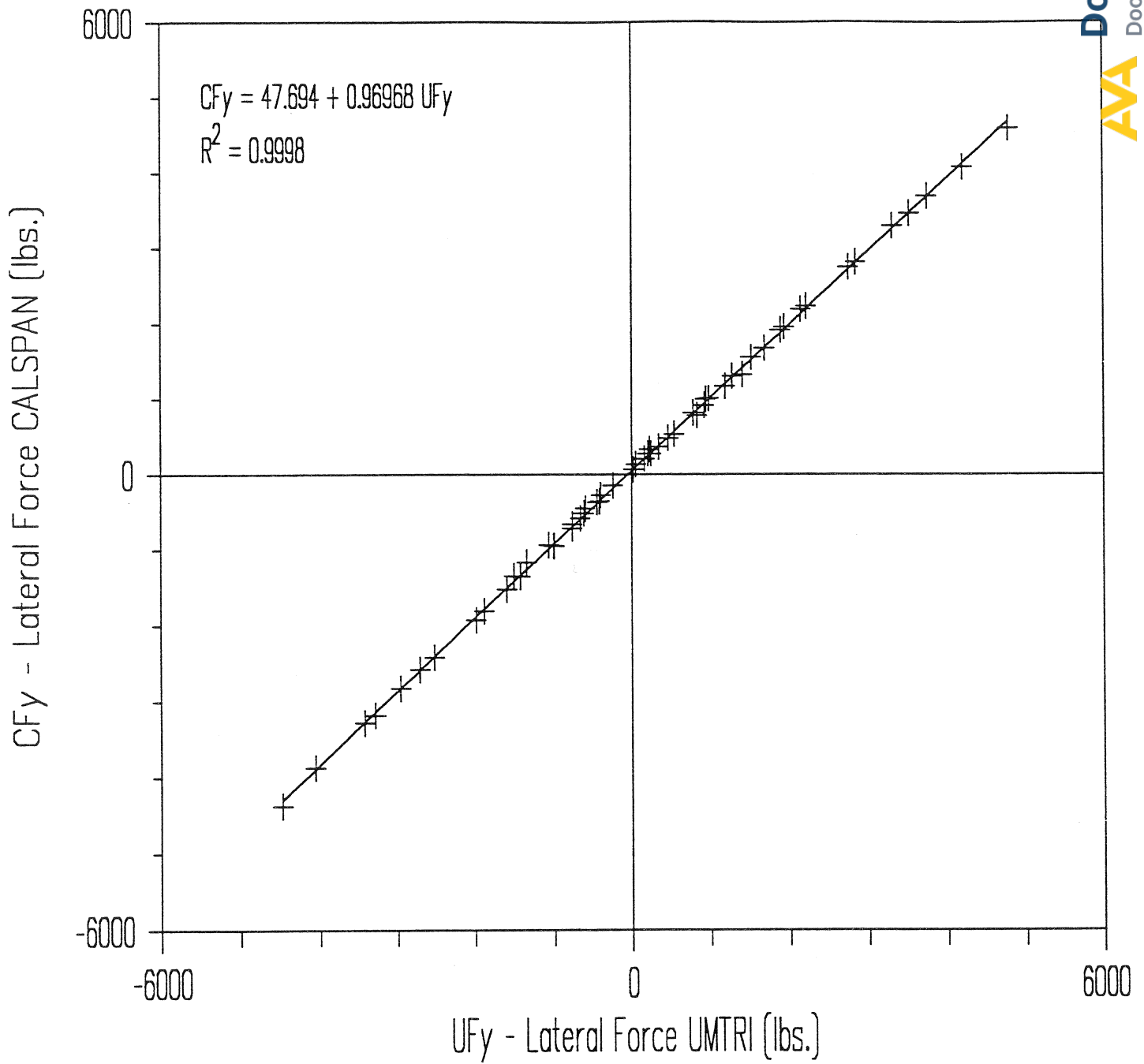


Figure 18 Detectable Differences for Aligning Moment

**Figure 19** CALSPAN and UMTRI Lateral Force Correlation

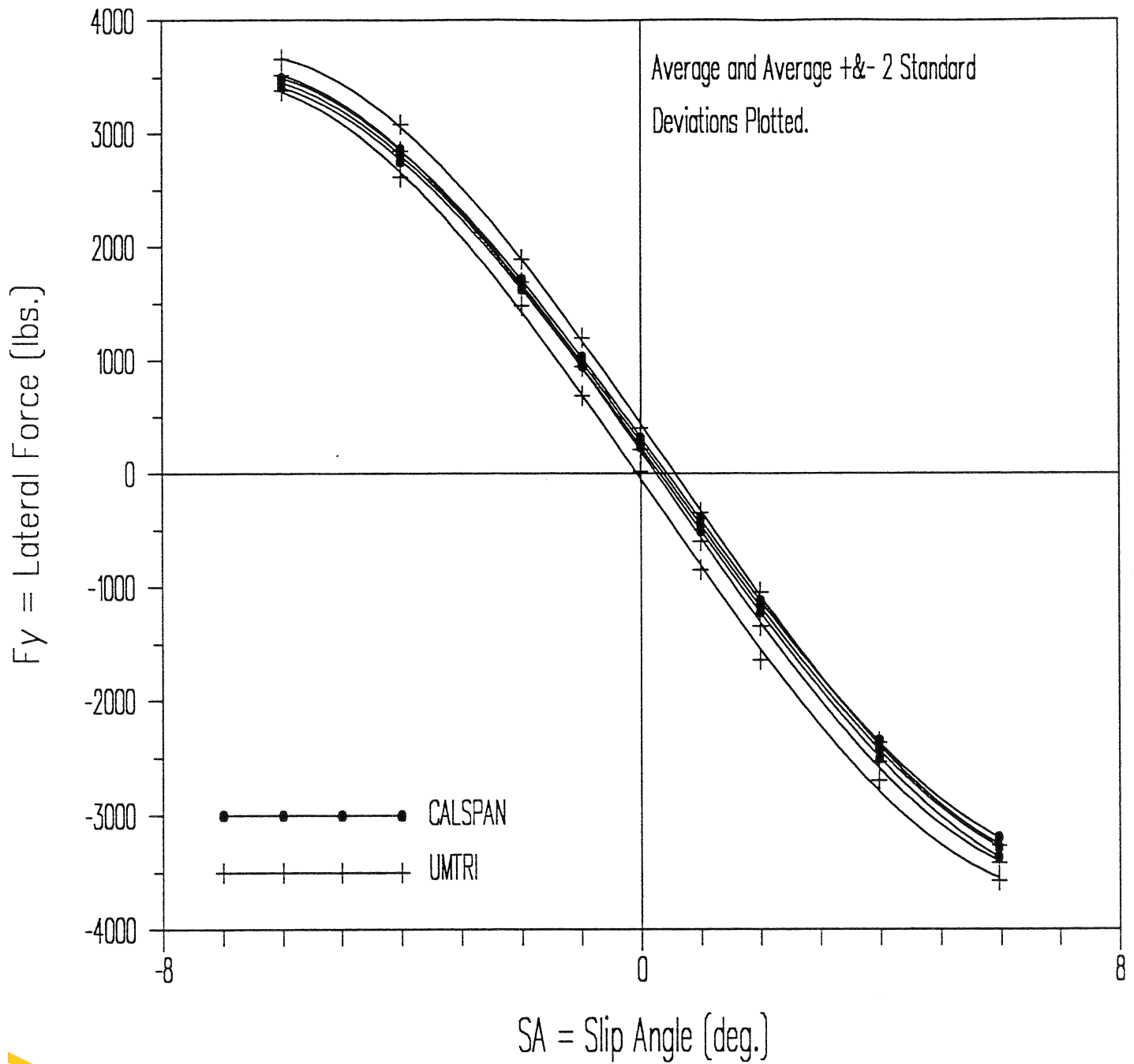
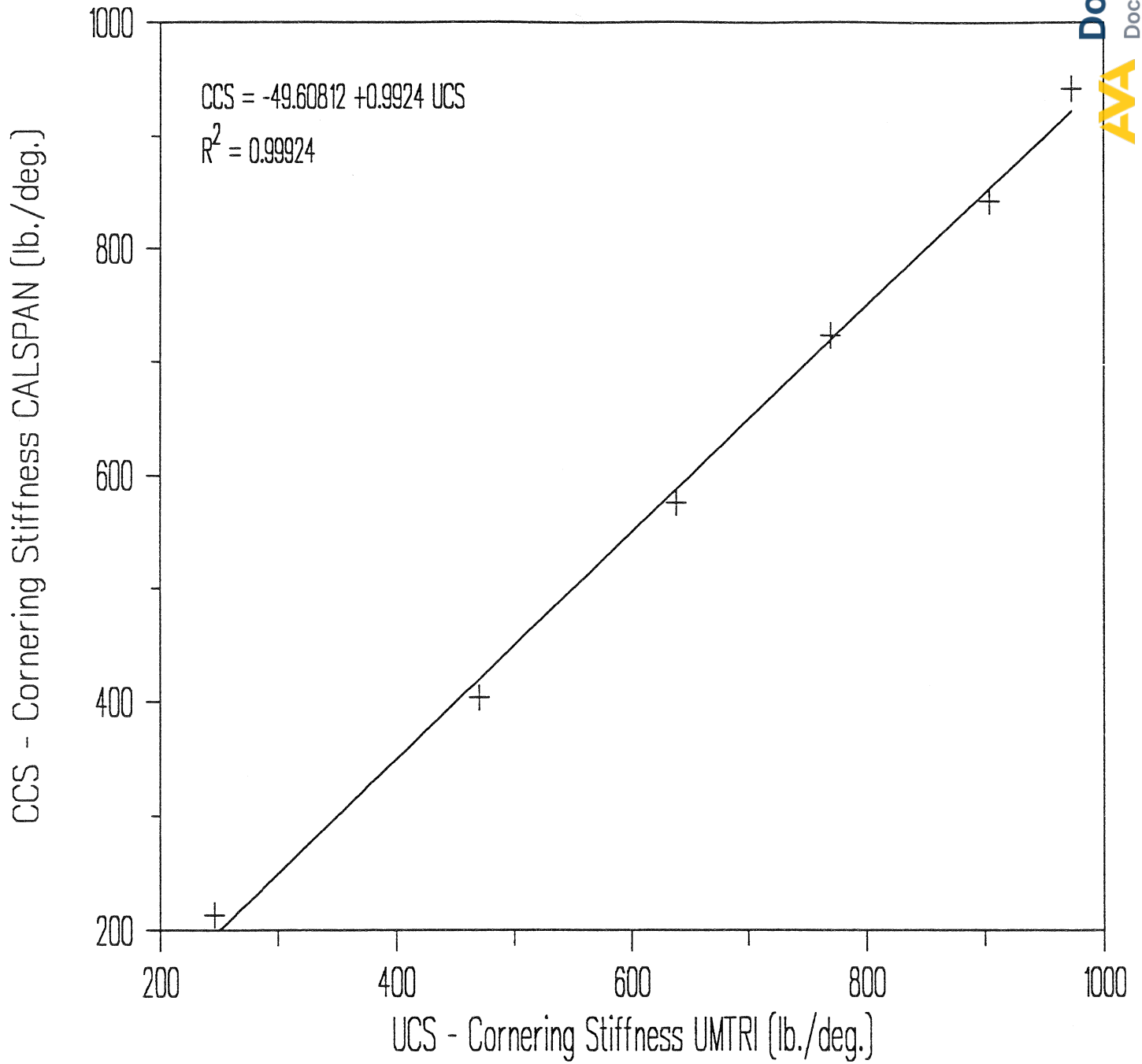


Figure 20 CALSPAN and UMTRI Lateral Forces Compared at Rated Load

**Figure 21** CALSPAN and UMTRI Cornering Stiffnesses Correlated

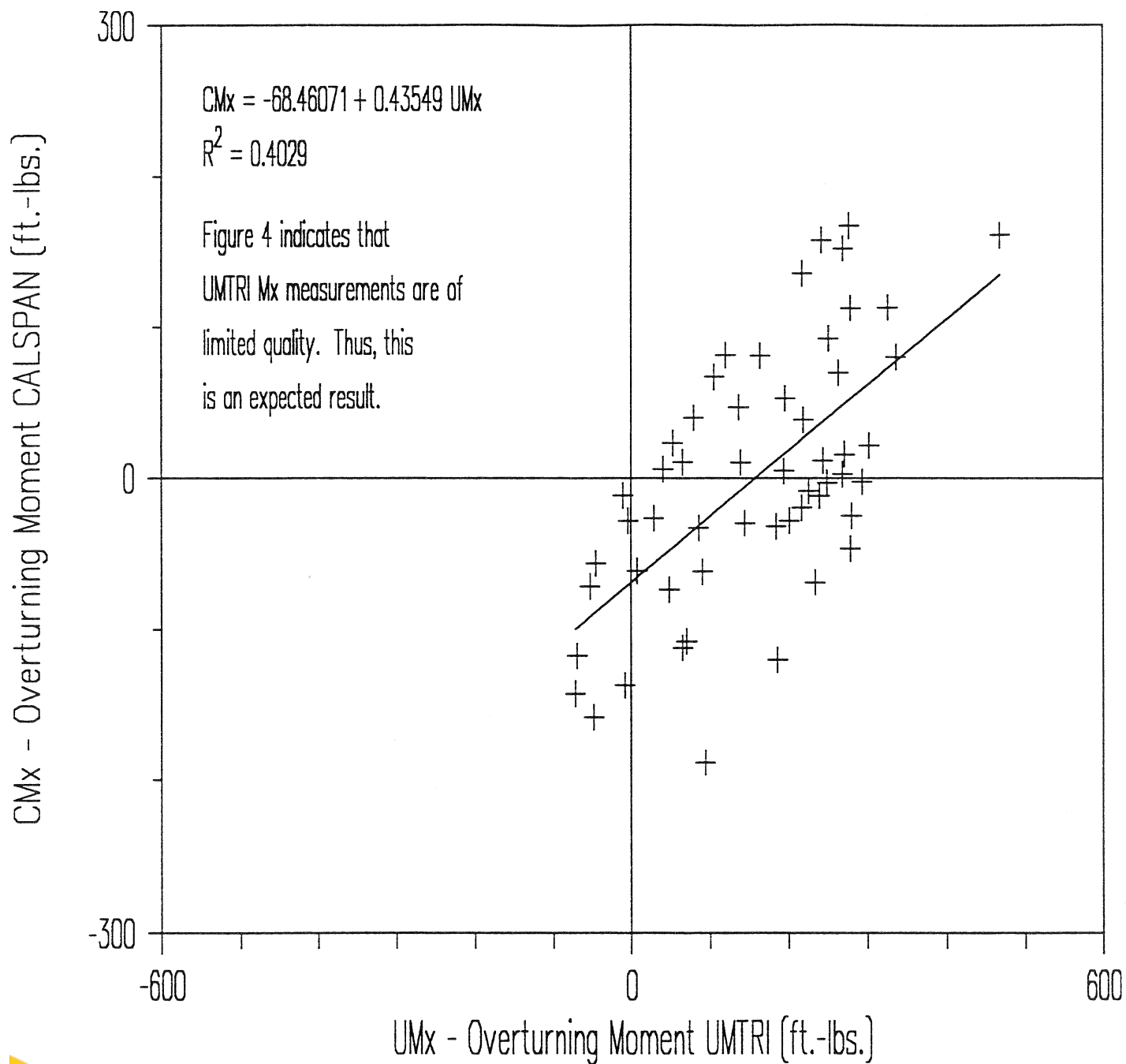


Figure 22 CALSPAN and UMTRI Overturning Moment Correlated

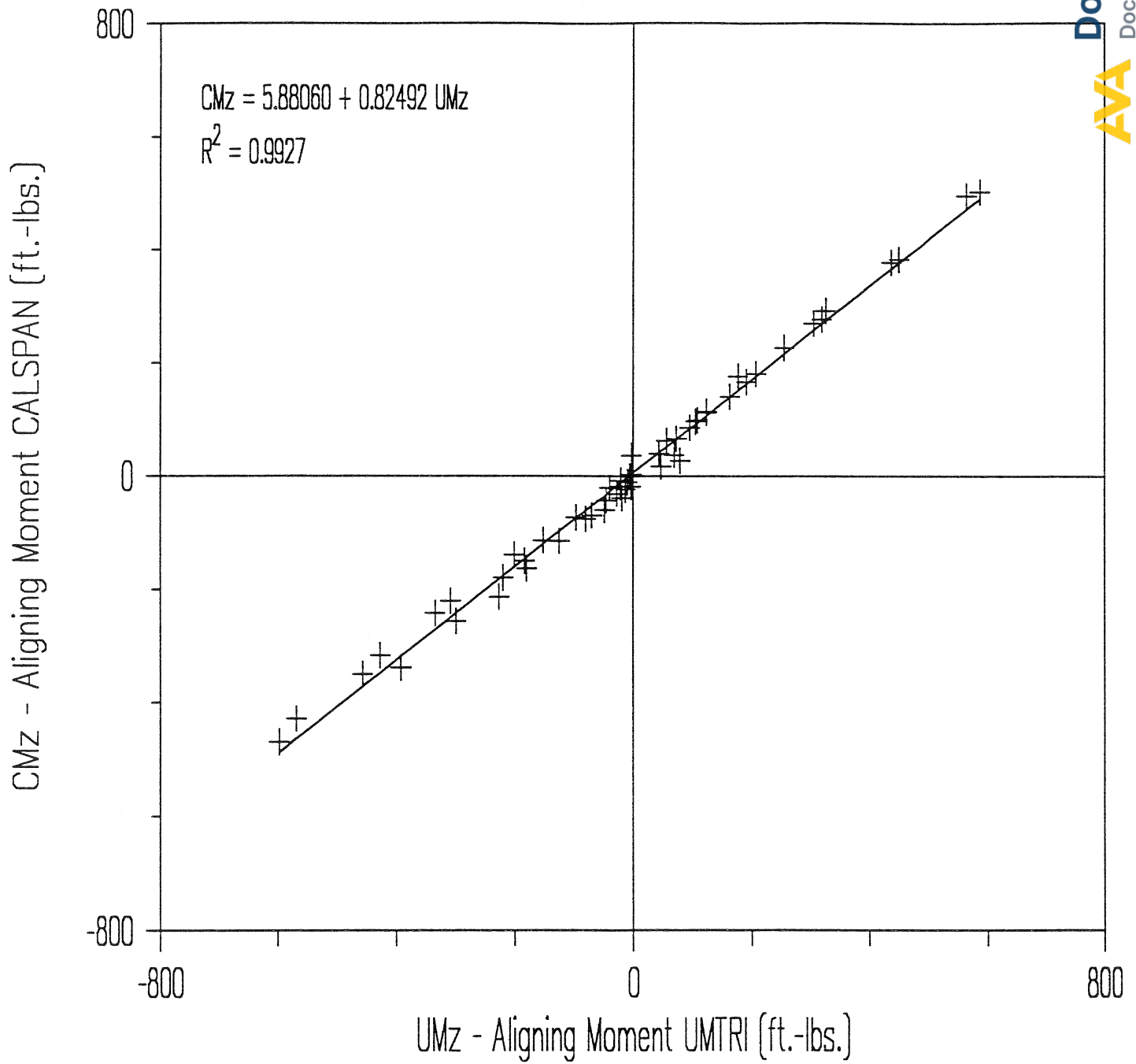


Figure 23 CALSPAN and UMTRI Aligning Moments Correlated

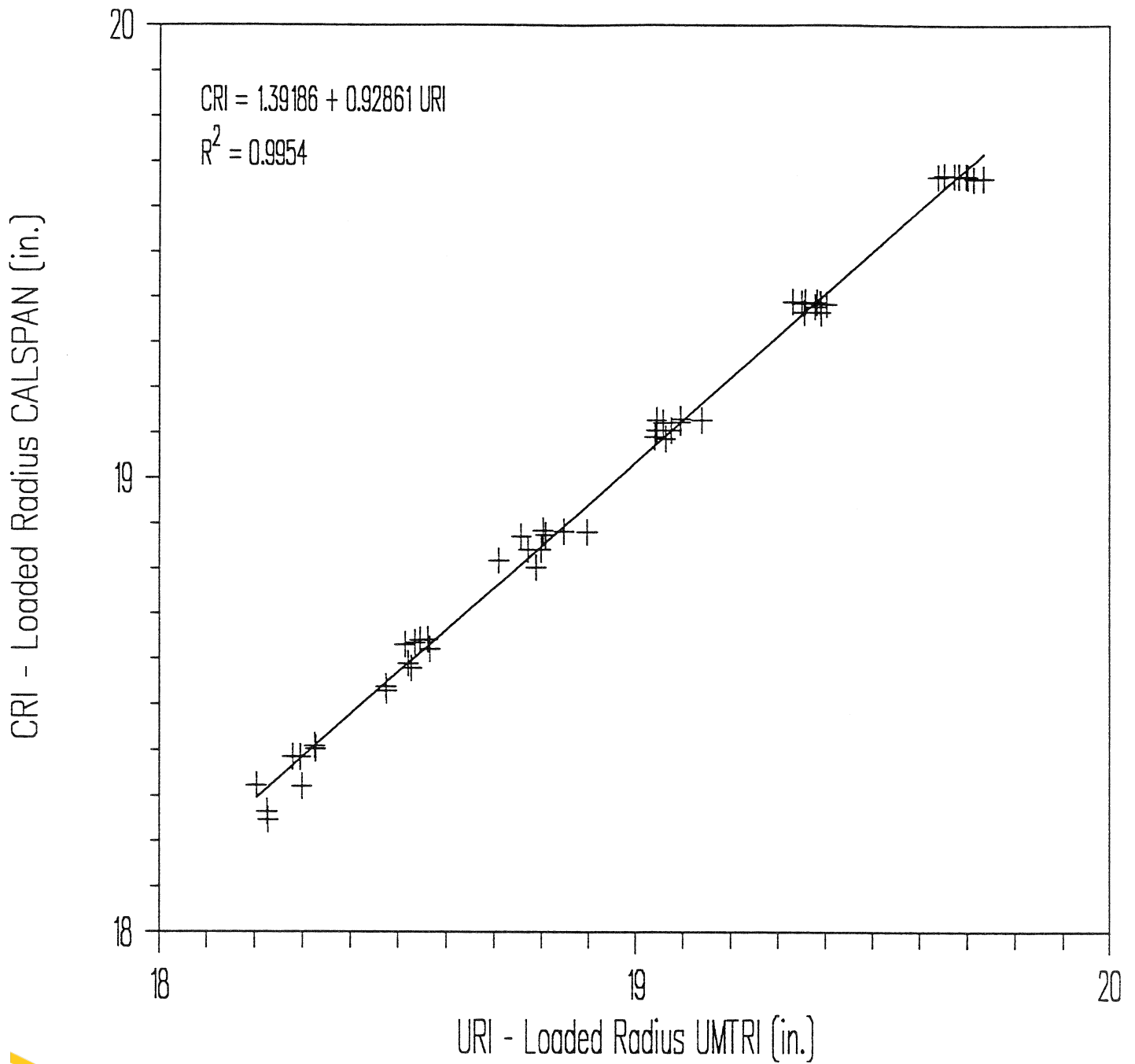


Figure 24 CALSPAN and UMTRI Loaded Radii Correlated



Sow 1.2.1 Final Report



SOW 1.2.1 Final Report

by

Marion G. Pottinger

SMITHERS SCIENTIFIC SERVICES, INC.

August 7, 1994

NOTE: Place this report at the front of a three ring binder with tabs for References IV, V, VI, and VII. This will form the SOW 1.2.1 report set arranged for the use of committee members selected to prepare the Free-Rolling Truck Tire Force and Moment Test Recommended Practice.

Foreword

The Final Report for Statement of Work Section 1.2.1 is a reference to the SOW 1.2.1 work for the use of the members of the Standards Committee which will produce a Recommended Practice for Free-Rolling Cornering Force and Moment Testing of Medium and Heavy-duty Truck Tires.

The Final Report for Statement of Work Section 1.2.1 is a summary document. This report does not contain the figures which are referenced. These figures appear in the reports which are referenced and bound by SAE along with this report in a three ring binder to form a set.

Contents

Test Procedure
Control Tires and Their Use
Limitations of the Test Equipment
Character of the Data
Statistical Considerations
Analysis Requirements
References

Test Procedure

The test procedure is as specified in the original SOW¹¹. The wording herein differs from the original SOW when the original wording was found to cause confusion during the SOW 1.2.1 testing or when experience with the SOW 1.2.1 testing has shown that a particular procedure should be modified.

AMBIENT TEMPERATURE

60°F < T_A < 80°F Tire properties depend on temperature. It was restricted to control variance.

INFLATION PRESSURE

The inflation pressure used in the test is a regulated inflation pressure. This section discusses determination and setting of the test inflation pressure.

1. Mount an experimental tire on the tire and rim standards organization specified rim.
2. Inflate the tire to the target cold inflation pressure specified by the test requester and cap the valve.

¹ Superscript roman numerals signify references.