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An SAE International Group

AEROSPACE RECOMMENDED PRACTICE

SAE ARP4955 REV. A

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Superseding ARP4955

(R) Recommended Practice for Measurement of Static and Dynamic Characteristic Properties of Aircraft Tires

RATIONALE

ARP4955A has been reaffirmed to comply with the SAE five-year review policy.

TABLE OF CONTENTS

1. SCOPE

The purpose of this SAE Aerospace Recommended Practice (ARP) is to establish guidelines for the measurement of static and dynamic characteristic properties of aircraft tires. It is intended as a general guide toward standard practice, but may be subject to frequent changes to keep pace with experience and technical advances.

This revision (Revision A) is also intended to provide suggested guidelines for synthesizing tire dynamic data necessary for landing gear shimmy analyses.

2. REFERENCES

2.1 Applicable Documents

The following publications form a part of this document to the extent specified herein. The latest issue of SAE publications shall apply. The applicable issue of other publications shall be the issue in effect on the date of the purchase order. In the event of conflict between the text of this document and references cited herein, the text of this document takes precedence. Nothing in this document, however, supersedes applicable laws and regulations unless a specific exemption has been obtained.

2.1.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or 724-776-4970 (outside USA), www.sae.org.

2.1.1.1 SAE J670e Vehicle Dynamics Terminology, 1976

2.1.1.2 SAE 1999-01-5527 An Investigation of Landing Gear Shimmy: Tire Models, Tire Test Methodologies, Analysis and Parameter Studies, John Medzorian, 1991

2.1.1.3 SAE 961300 Relaxation Behavior of Aircraft Tires, C. B. Alsobrook and M. G. Vogel, 1996

2.1.1.4 SAE 2005-01-3438 Mechanical Properties of Radial-Ply Aircraft Tires, John Tanner, Robert Daugherty, Henry Smith, 2005

2.1.2 NASA Publications

Available from NASA, Documentation, Marshall Space Flight Center, AL 35812, www.nas.nasa.gov.

2.1.2.1 NASA TR R-64 Mechanical Properties of Pneumatic Tires with Special Reference to Modern Aircraft Tiress, Robert Smiley, Walter Horne, 1960

2.1.2.2 NASA TP 1863 Static and Yawed Rolling Mechanical Properties of Two Type VII Aircraft Tires, John Tanner, Sandy Stubbs, John McCarty, 1981

2.1.2.3 NASA TP 1917 Cornering of the Nose-Gear Tire of the Space Shuttle Orbiter, William Vogler, John Tanner, 1981

2.1.2.4 NASA TM 1999-209141 Quasi-Static Viscoelastic Finite Element Model of an Aircraft Tire, Arthur Johnson, John Tanner, Angela Mason, 1999

2.1.2.5 NASA TM 2003-212415 A Study of the Mechanical Properties of Modern Radial Aircraft Tires, Robert Daugherty, 2003

2.1.3 U.S. Government Publications

Available from the Document Automation and Production Service (DAPS), Building 4/D, 700 Robbins Avenue, Philadelphia, PA 19111-5094, Tel: 215-697-6257, http://assist.daps.dla.mil/quicksearch/.

2.1.3.1 MIL-PRF-5041 Military Specification for Tires, Pneumatic, Aircraft

2.1.3.2 DOT HS 905 952 Mechanics of Pneumatic Tires, Samuel Clark, 1981

2.2 Other Applicable References

2.2.1 J. of Aircraft, Vol.8, No. 9 Synthesis of Tire Equations for Use in Shimmy and Other Dynamic Studies; L. C. Rogers, H. K. Brewer, 1971

2.2.2 J. of Aircraft, Vol. 6, No. 3 Tire Parameters for Landing-Gear Shimmy, R. L. Collins, R. J. Black, 1969

2.3 Symbols

A_1 constant depending on initial tire distortion

A_2 constant depending on the initial lateral force

A_{fy} side force amplitude ratio

A_{mz} aligning moment amplitude ratio

C_ψ cornering stiffness

C_1 zero offset

C_2 initial tire lateral force

D_{fy} $-\tan(\delta_{fy}) > 0$

D_{mz} $-\tan(\delta_{mz}) > 0$

F_0 steady state force

F_d drag force (parallel to the wheel plane)

F_s side force (perpendicular to the wheel plane)

F_x fore and aft force

F_y lateral force

F_z vertical load

H tire footprint half length

h loaded radius, axle height

K_l lateral stiffness

K_t torsional stiffness

K_x	fore and aft stiffness
L	relaxation length
L_f	unyawed rolling relaxation length
L_y	yawed-rolling relaxation length
M_{fy}	$A_{fy} > 0$
M_{mz}	$-A_{mz} > 0$
M_x	overturning moment
M_y	brake torque
r	tire undeflected radius
R_{BT}	brake torque radius
r_e	effective rolling radius
r_{eb}	effective braked rolling radius
r_{ey}	effective yawed rolling radius
t	time
V	horizontal velocity of wheel
x	distance rolled
x_c	fore-aft shift of the center of pressure
y'_c	lateral shift of the center of pressure
α	wheel slip angle = angle between SAE X axis and velocity of wheel plane on ground vector (rad)
α_a	maximum amplitude of twist during oscillation
α_m	mean tire twist
Δ	lateral displacement of footprint
δ	tire deflection
δ_{mz}	aligning moment phase angle
δ_{fy}	side force phase angle
ϕ	phase angle
η_t	torsional damping coefficient
η_x	fore and aft damping coefficient

λ wavelength = yaw oscillation frequency / longitudinal velocity

θ_a wheel yaw amplitude

ψ yaw angle

ψ_t tire twist angle

Ω angular velocity of wheel

ω yaw rate

3. TIRE PREPARATION

3.1 Tire Conditioning

Before break-in, the tire shall be conditioned by mounting on its design rim and inflating it to the rated inflation pressure. The tire shall be allowed to remain in this condition for 24 h at an ambient temperature ranging from 60 to 100 °F (15.6 to 37.8 °C).

3.2 Tire Inflation and Ambient Temperature

After the tire has been conditioned for 24 h on the design rim as indicated in 4.1, the tire pressure shall be readjusted to the rated inflation pressure with a gauge which has been calibrated to within 1%. All tests shall be carried out at temperatures range of 60 °F (15.6 °C) to 100 °F (37.8 °C).

3.3 Break-in Procedure

3.3.1 Break-in Procedure - Static Testing Only

This method of tire break-in prepares the test tire by inflating it to rated inflation pressure and loading the tire under direct vertical load against a hard, flat, unyielding surface to the point that the tire deflection measures 50% of the section height. The load is then removed. This load-deflection procedure is carried out five times each at two locations equally spaced around the tire, with the centerline of the contact patch being located at 180 degree intervals around the circumference of the tire. When the tire has been unloaded for 1 h or more, the break-in procedure should be repeated before resuming static loading testing. Figure 1 illustrates the effect of this break-in procedure on the hysteresis characteristics of the tire vertical load-deflection curve.

3.3.2 Break-In Procedure - Dynamic or Alternate Static Testing

This method of tire break-in prepares the test tire by inflating it to rated inflation pressure, corrected for flywheel curvature, then performing five rated load take-off cycles of a load-speed-time curve representative of the applicable aircraft.

4. STATIC PROPERTY TESTS

4.1 Loading Apparatus

The tire is to be mounted on either a suitable yoke or a mandrel and loaded vertically against a hard, flat, unyielding surface under a camber angle of 0° ± 1/4°, and under a caster angle of 0° ± 1/4° (see Figure 2). The load measuring system shall be accurate within ±1% of the load applied to the tire. If a mandrel type axle is used in the testing equipment, compensation should be made for the resulting axle deflection created during the loading of the tires.

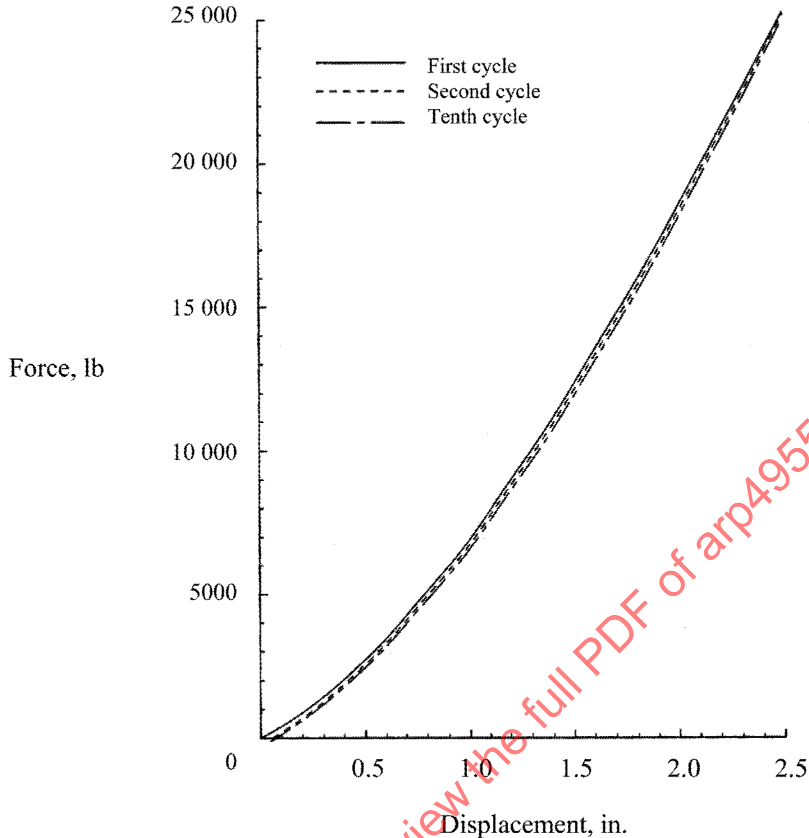

FIGURE 1 - LEAST-SQUARES APPROXIMATION OF HYSTERESIS LOOPS DURING CYCLIC LOADING

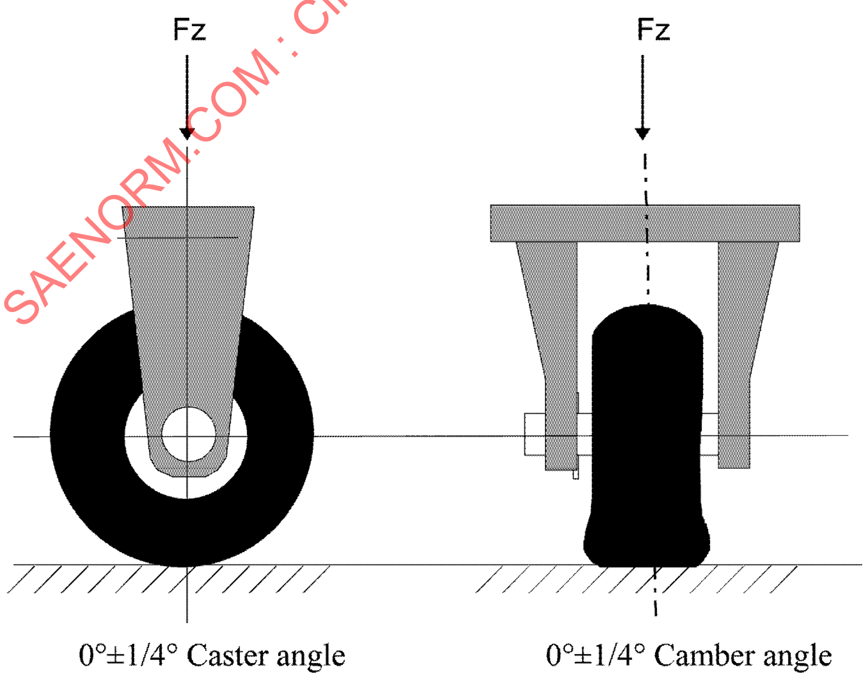

FIGURE 2 - LOAD MACHINE CONFIGURATION

4.1.1 Loading Plate

The surface of the plate in contact with the tire shall be a smooth metal plate. Other surfaces may be used in lieu of this surface but must be noted with the reporting of the data.

Any contamination of the prepared surface of the plate should be removed prior to each load application to maintain a uniform friction coefficient.

4.2 Vertical Load Deflection Curves

This recommended practice is based on the measurement of load deflection curves at rated inflation pressure. It should be understood that any inflation pressure may be used for this test, and it is left to the specification of the user to define pressures other than rated pressures. Accordingly, such load deflection curves as are described in this section shall clearly state the inflation pressure at which they were obtained.

4.2.1 Vertical Load Deflection Curves

Vertical load deflection curves shall be obtained on the inflated tire by means of applying a vertical load designated F_z in Figure 2, and measuring the corresponding deflection between the wheel flange and the unyielding flat surface against which the tire acts. The load will be applied beginning from the point of contact of the tire with the flat surface until such time as the tire bottoms, with continuous recording of load, inflation pressure and corresponding deflection. Load will then be reduced until its value returns to zero, again continuously monitoring load, inflation pressure, and corresponding deflection. The total load deflection loop or curve shall be presented as indicative of the vertical load deflection characteristics of the tire.

This test shall be carried out at two locations around the tire 180 degrees apart. Each vertical load deflection test shall be performed at the opposite location of the last loading to minimize the effect of a flat spot.

The time rate of the tire deflection shall not be more than 2.0 in/min (50.8 mm/min).

4.2.2 Vertical Spring Rate

The vertical spring rate is defined as the spring constant associated with the average slope of a line tangent to the load deflection curve during loading at a specified deflection (preferably rated deflection). It is derived from the vertical load deflection curves created according to 4.2.1.

4.2.3 Bottoming Point

The tire bottoming point is the point at which the tire has fully deflected its sidewall and is beginning to compress the lower sidewall structure. This is recognized by a noticeable change in the slope of the load deflection curve occurring at a high load and deflection. The bottoming point is the load and deflection at that point.

4.2.3.1 Applicable Range of Measured Parameters

Bottoming point should be measured at the rated inflation pressure for the application. Additional inflation pressures may be required by the investigator for additional operating parameters.

4.2.3.2 Procedure for Approximating Bottoming Point

4.2.3.2.1 For the purpose of approximating bottoming load for a given tire and given inflation, the bottoming load shall be considered to be that load at which the rate of loading (lb/in) is 2.2 times the average rate of loading between 28% and 48% vertical deflection.

4.2.3.2.2 The bottoming load is determined as follows (see Figure 3):

a. Conduct load deflection testing as described in 4.2.1, obtaining sufficient data to plot a representative curve for the inflation pressure required.

b. Plot the load deflection curve.

c. Calculate the inverse slope (lb/in) between 28% and 48% deflection
(Figure 3 example: 14,600 / 1.46 = 10,000 lb/in)

d. Construct a straight line (A-A) having a slope (lb/in) equal to 2.2 times that of c. (e.g., 2.2 X 10,000 = 22,000 lb/in).

e. Draw line B-B parallel to A-A and tangent to the load deflection curve in the bottoming area.

f. The bottoming load will be considered that value which occurs at the point of tangency (P).

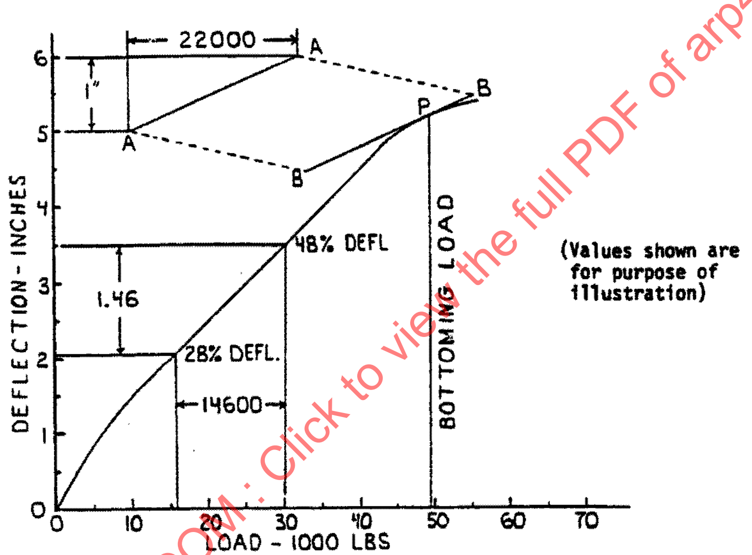

FIGURE 3 - APPROXIMATION OF BOTTOMING POINT

4.2.3.3 Alternate Procedure for Determining the Bottoming Point

a. Adhere two 1.5 in (38.1 mm) wide thin metal strips with wire leaders attached, to the inside of the tire in the configuration shown in Figure 4.

b. Mount the tire and inflate to the specified test pressure. Locate the strips in the center of the footprint and load the tire at a rate not exceeding 2.0 in/min (50.8 mm/min) until continuity is indicated on the ohmmeter. This indicates the metal strips are in contact with each other and the tire has reached its bottoming point. Record the load, deflection, and pressure at this point.

4.3 Non Rolling Lateral Load - Deflection Curves

4.3.1 Definition of Lateral Deflection

The lateral deflection of the tire is the relative lateral displacement between the wheel flange at a point immediately above the centerline of the tire contact patch, and the loading plate, parallel to the loading plate surface. This displacement is along the SAE Y axis from the wheel center plane on the ground and the tire footprint geometric center. The SAE vehicle axis system is defined in Reference 2.1.1.1 as a right-hand orthogonal system such that forward motion is along the SAE X axis, the SAE Y axis points to the right and the SAE Z axis points downward.

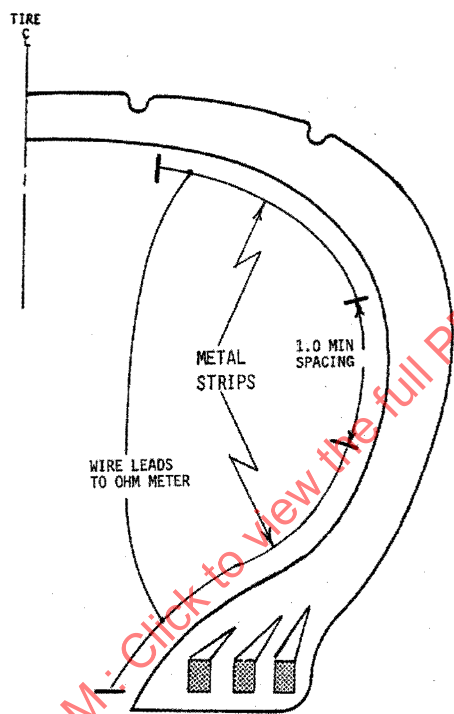

FIGURE 4 - LOCATION OF METAL STRIPS

4.3.2 Obtaining Lateral Load Deflection Curves

The surface of the plate in contact with the tire shall be covered with a material designed to prevent tire slippage, insofar as possible. Lateral load deflection curves shall be obtained by first loading the inflated tire as described in 3.1 to the rated deflection under rated load conditions, followed by lateral displacement of the tire yoke or the flat surface against which the tire rests in a direction perpendicular to the wheel plane. The lateral displacement may be obtained either by displacement of the yoke or the flat surface or both. Care must be taken to account for any structural deflections of the tire mounting fixture during these tests.

Quasi-static load deflection curves will be obtained by increasing the lateral load from zero to a value equal to 30% of the applied vertical load, then by decreasing this lateral load to zero and increasing it in the opposite direction to 30% of the applied vertical load, and finally returning to 30% of the rated vertical load, completing the loop (in Figure 5, O - A - B - A). It is suggested that this loading sequence be repeated three times to insure that the hysteresis loop is repeatable. Load, pressure, and lateral deflection will be continuously recorded. This lateral hysteresis loop, Figure 5, shall be obtained at a deflection rate of not more than 2.0 in/min (50.8 mm/min).

These lateral load deflection curves will be obtained at two points around the periphery of the tire, separated by 180 degrees, and representing the centerline of the contact patch under loaded conditions. All curves will be performed as indicative of the tire lateral load deflection characteristics.

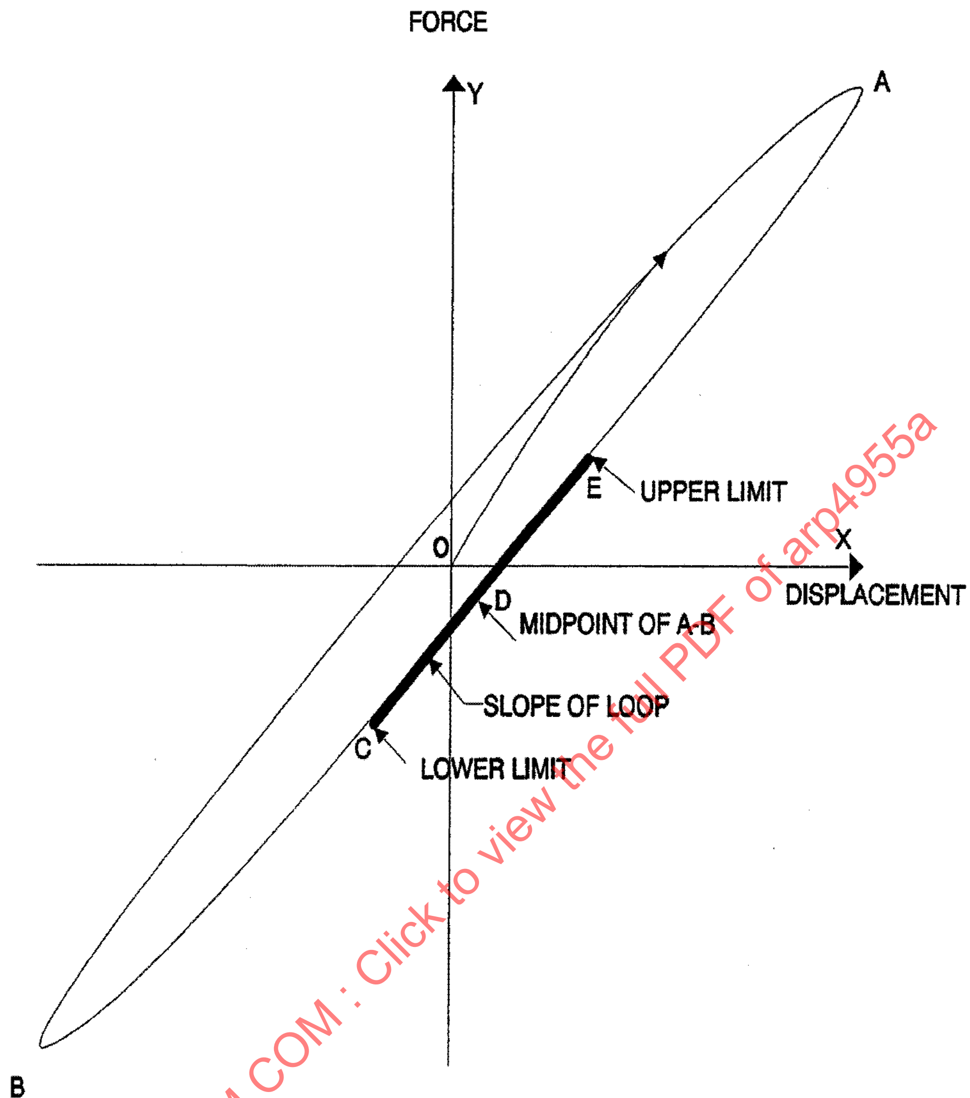

FIGURE 5 - TYPICAL LATERAL AND FORE-AFT HYSTERESIS LOOP

4.3.3 Obtaining Lateral Damping

Cyclically varying the lateral deflection at a given sinusoidal rate and measuring the phase angle between the load and deflection is a measure of lateral damping. This test should be performed at several rates of interest while keeping the lateral load less than 30% of the applied load throughout the test. A reasonable approximation of the damping coefficient is $\eta_y = \tan\phi$.

4.3.4 Lateral Spring Rate

The lateral spring rate is defined as the slope of the lower leg of the hysteresis loop around the midpoint (D) of the maximum and minimum displacement to a point 10% greater (E) and 10% less (C) than the midpoint value (Figure 5).

4.3.5 Vertical Sinkage

During this process of lateral deflection, the vertical load of the tire will change somewhat, unless appropriate correction is made. It is specifically intended that these be monitored and adjusted to a constant value equal to the rated load during the conduct of this test.

The vertical sinkage of the tire accompanying this vertical load adjustment should be measured and recorded using the same vertical deflection measuring techniques as in 4.2.1. It should be presented as a plot of vertical sinkage versus lateral deflection with the accompanying vertical load and inflation pressure clearly stated.

4.4 Measurement of Shift of the Contact Patch Centroid During Lateral Loading

During the course of the lateral deflection process, the centroid of the tire vertical force in the contact patch will shift a distance from the geometric center of the footprint. It is desirable to obtain a measurement of this distance. This can be done in one of two ways:

a. Preferably, the loading plate can be instrumented with multiple load cells so that the position of the centroid of vertical forces may be determined accurately by appropriate recording of the load cell signals, followed by sufficient data processing to solve for the unknown centroid of vertical forces.

   or

b. For loading machines with axles instrumented for force measurements, lateral shift (y_c) can be determined from the following equation (Reference Figure 6):

$$y'_c = \frac{M_x - F_s h}{F_z} \qquad \text{(Eq. 1)}$$

where:

F_s = side force (perpendicular to the wheel plane)

F_z = vertical load

h = loaded radius (< or = static loaded radius)

M_x = overturning moment

y'_c = lateral center of pressure shift (relative to wheel plane)

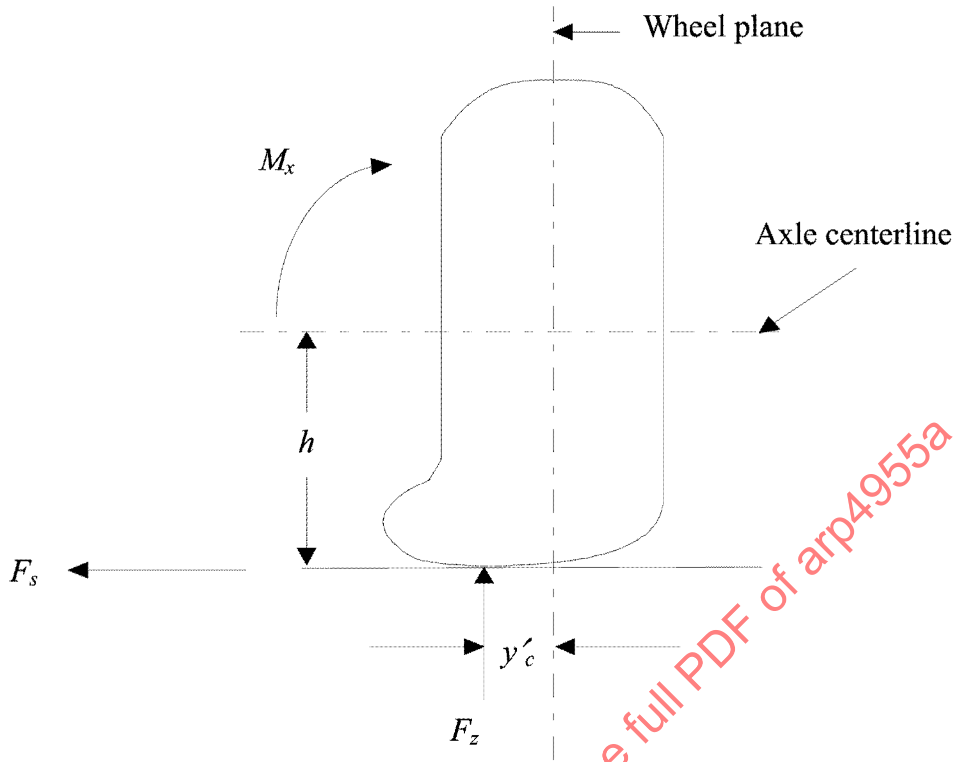

FIGURE 6 - FORCES AND MOMENTS IN VERTICAL PLANE PERPENDICULAR TO WHEEL PLANE

4.5 Non-Rolling Fore and Aft Load Deflection Curves

4.5.1 Definition of Fore-Aft Deflection

The non-rolling fore-aft deflection is the relative displacement along the SAE X axis from the wheel center plane on ground and the footprint geometric center.

4.5.2 Method for Determining Fore-Aft Load Deflection Curves

The surface of the plate in contact with the tire shall be covered with a material designed to prevent tire slippage, insofar as possible. The tire should be inflated to rated pressure with vertical loading equal to the rated load. The wheel should be restrained from rotating and marked in relationship to the tire to indicate any tire/wheel slippage. The fore-aft displacement may be obtained either by displacement of the yoke, or of the loading plate or both. Care must be taken to account for any structural deflections of the tire mounting fixture during these tests.

Load deflection curves will be obtained by increasing the fore-aft load from zero to a value equal to 15% of the applied vertical load, then by decreasing this fore-aft load to zero and increasing it in the opposite direction to 15% of the applied vertical load, and finally returning to 15% of the rated vertical load, completing the loop (in Figure 5, O - A - B - A). It is suggested that this loading sequence be repeated three times to insure that the hysteresis loop is repeatable. Load, pressure, and fore-aft deflection will be continuously recorded. The total fore and aft hysteresis loop shall represent the fore-aft deflection characteristics of the tire. Two such loops should be obtained, one each at two positions located 180 degrees apart around the circumference of the tire. The rate of loading during the fore-aft process shall not be more than 2.0 in/min (50.8 mm/min).

4.5.3 Obtaining Fore and Aft Damping

Cyclically varying the fore-aft deflection at a given sinusoidal rate and measuring the phase angle between the load and deflection is a measure of longitudinal damping. Perform this test at several rates of interest while keeping the fore-aft load less than 15% of the vertical load throughout the test. A reasonable approximation of the damping coefficient is $\eta_x = \tan \phi$.

4.5.4 Fore-Aft Spring Rate

The fore-aft spring rate is defined as the slope of the lower leg of the hysteresis loop around the midpoint (D) of the maximum and minimum displacement to a point 10% greater (E) and 10% less (C) than the midpoint value (Figure 5).

4.5.5 Vertical Sinkage

During this process of fore-aft deflection, the vertical load of the tire will change somewhat, unless appropriate correction is made. It is specifically intended that these be monitored and adjusted to a constant value equal to the rated load during the conduct of this test.

The vertical sinkage of the tire accompanying this vertical load adjustment should be measured and recorded using the same vertical deflection measuring techniques as in 4.2.1. It should be presented as a plot of vertical sinkage versus fore-aft deflection with the accompanying vertical load and inflation pressure clearly stated.

4.6 Measurement of the Shift of the Contact Patch Centroid During Fore-Aft Loading

During the process of fore-aft loading of the tire, the centroid of tire vertical load shifts in the fore-aft direction about the geometric center of the footprint. It is desirable once more to obtain measurements of such shift for design purposes. This can be done by either:

a. Suitable load cell instrumentation of the loading plate so that the shift of the centroid of vertical forces may be obtained.

   or

b. For loading machines with axles instrumented for force measurements, fore-aft shift can be determined from the following equation (Reference Figure 7):

$$x_c = \frac{F_d h - M_y}{F_z} \quad \text{(Eq. 2)}$$

where:

F_d = drag force (parallel to the wheel plane)

F_z = vertical load

h = loaded radius (< or = static loaded radius)

M_y = brake torque (equals 0 for steady state free rolling)

x_c = fore-aft shift of the center of pressure

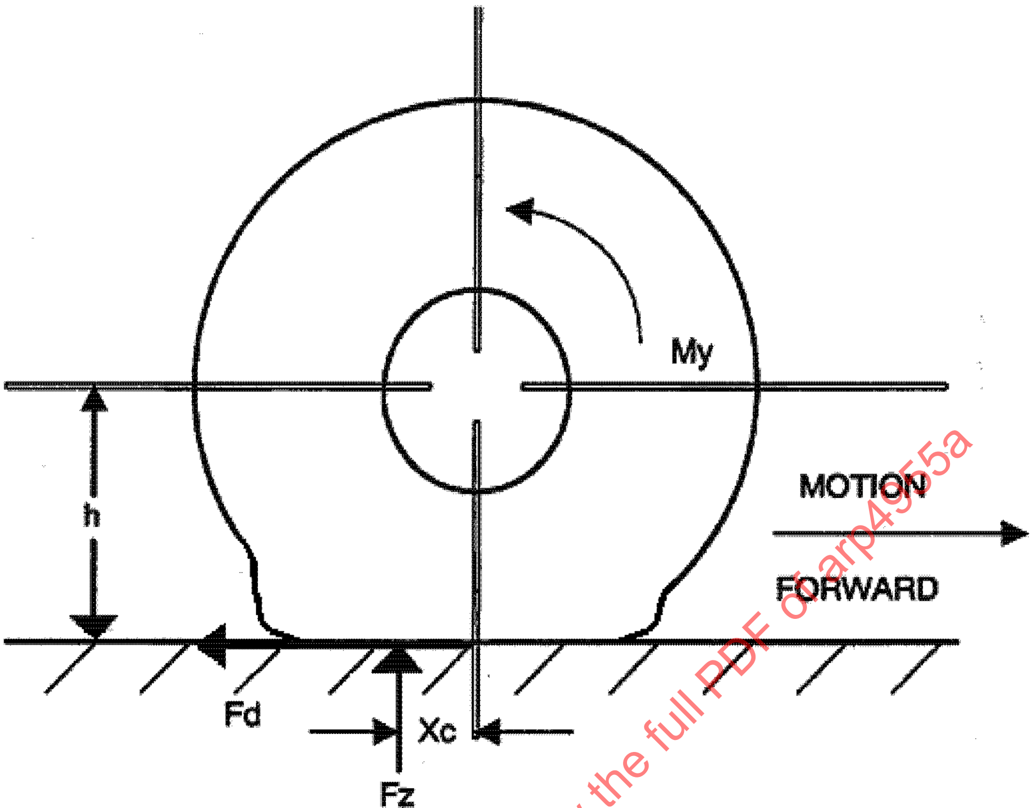

FIGURE 7 - FORCES AND MOMENTS IN VERTICAL PLANE PARALLEL TO WHEEL PLANE

4.7 Measurement of Brake Torque Radius

The brake torque radius is defined as the ratio of the brake torque to the tire brake force. This can be determined from the previous procedure of 4.6 and can be calculated as follows:

$$R_{BT} = \frac{M_y}{F_d} \quad \text{(Eq. 3)}$$

where:

R_{BT} = brake torque radius

M_y = brake torque

F_d = drag force (parallel to the wheel plane)

4.8 Non-Rolling Torsional Load Deflection

The torsional deflection of a non-rotating tire about its vertical axis will be defined as the angular displacement between the wheel plane and the longitudinal centerline of the tire's contact patch.

4.8.1 Equipment Description

A loading apparatus similar to that described in 4.1 can be used, except that a torsional displacement capability shall be incorporated either by rotation of the yoke or the flat loading surface.

The surface of the loading plate in contact with the tire shall be a smooth metal surface. This smooth surface is required to produce a full sliding condition in order to establish the maximum torsional load (Reference 2.1.3.2, page 571).

4.8.2 Applicable Range of Measured Parameters

Torsional load/deflection loops should be obtained at tire rated load and rated inflation pressure. The investigator may require additional load and pressure test combinations.

4.8.3 Test Procedure

The tire should be prepared for testing per Section 3.

4.8.3.1 Establish Maximum Torque

Load the tire to the specified vertical test load, followed by rotary motion between the tire yoke and the flat surface against which the tire is loaded. Continue this rotary motion until the maximum torque is reached. Record the maximum torque and report the angle of torsion at which the onset of maximum torque begins (Figure 8).

4.8.3.2 Required Test Torque

The required test torque is selected at some percentage of the maximum torque. It is recommended that two torque values, ±30 and ±80% of the maximum torque, be used for the required test torques. An additional test at a torsional angle of 2 degrees may provide insight on tire energy absorption characteristics under typical operational conditions.

4.8.3.3 Torsional Load-Deflection Loop

At the specified vertical load and the test inflation pressure, a torsional load-deflection loop is obtained by increasing the torque from zero up to the required test torque, then by decreasing this torque to zero and increasing it in the opposite direction to the required test torque, and finally completing the loop by returning to the required test torque (in Figure 9, O - A - B - A). It is suggested that this loading sequence be repeated three times to insure that the hysteresis loop is repeatable. Load, pressure, and torque will be continuously recorded.

The rate of the tire's torsional deflection shall not be more than 3 degrees per second.

The surface of the loading plate must be cleaned after each torsional load application. Rubber contamination on the loading plate will affect the results.

This test shall be carried out at two locations around the tire's circumference, each separated by 180 degrees.

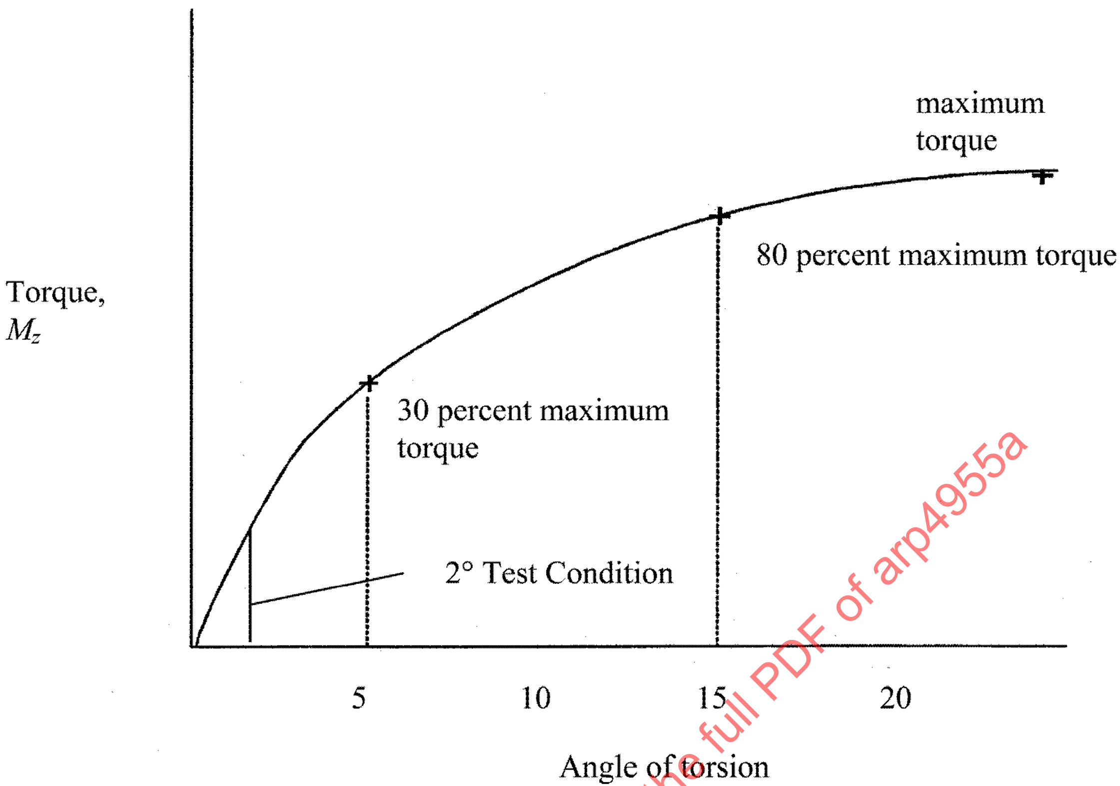

FIGURE 8 - TORSIONAL STIFFNESS CHARACTERISTICS

4.8.4 Data Reduction

Torque in lbs-ft versus angle of torsion in degrees will be required to establish the maximum torque at which slippage occurs for each specified test tire load and pressure combination.

Torsional hysteresis loops obtained at each required test torque would be adequate for obtaining the torsional stiffness of the tire. The torsional stiffness is the average slope of the line tangent to the downward portion of the torsional hysteresis loop (in Figure 9, C-D-E). Tire load, inflation pressure, and the torsional rate should be noted on all plots.

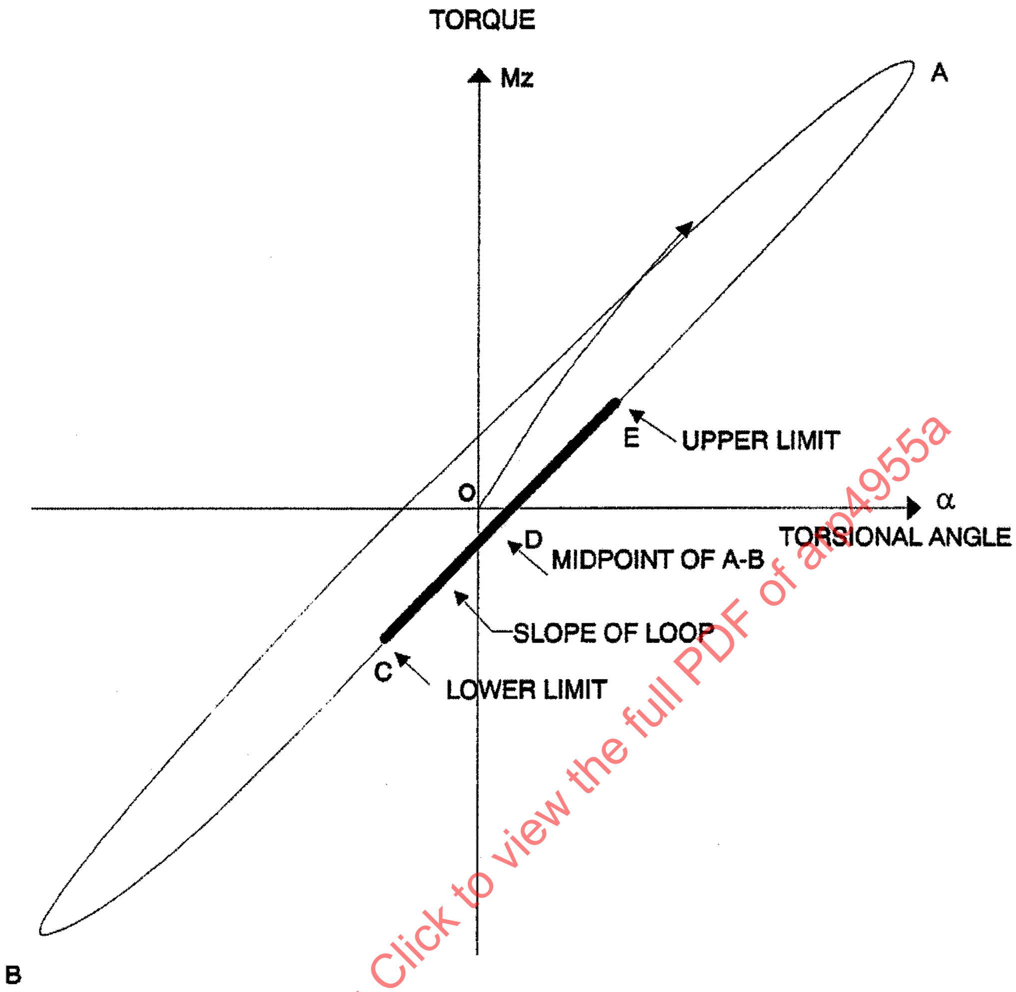

FIGURE 9 - TORSIONAL HYSTERESIS LOOP

5. ROLLING TIRE MECHANICAL PROPERTY TESTS

5.1 Yawed-Rolling Relaxation Length

Yawed-rolling relaxation length is the distance which a tire must roll in order to reach 63.2% of its steady state cornering force when stepped to a given yaw angle.

It is important to note that the relaxation length can vary significantly with both the yaw angle and vertical deflection. A complete characterization of tire behavior therefore requires that relaxation be characterized over the operating range to be modeled.

5.1.1 Equipment Description

Testing will entail accurate measurement of lateral force as a function of roll distance and yaw. The test machine must generate accurate lateral force and roll distance data. Relaxation length can be most simply determined by plotting F_y versus x and measuring the x where F_y is equal to 63.2% of the maximum level. This method has the advantage of simplicity but tends to be rather subjective, especially when the data is noisy. The preferred method involves nonlinear regression over the most stable region (the rising portion of the curve), as described in 5.1.4. Reference 2.1.1.3 shows a typical test setup for measuring tire relaxation lengths.

5.1.2 Applicable Range of Measured Parameters

Relaxation length is described in Reference 2.1.2.1 as varying with vertical deflection. No mention of the effect of variation in yaw angle on relaxation length is made in Reference 2.1.2.1, but this effect may be more significant than the vertical deflection effect. Variation in relaxation length as a function of yaw angle is illustrated in Figure 10.

Relaxation length should be measured at the most critical conditions of yaw angle and vertical deflection plus enough additional conditions to permit accurate predictions over the required parameter range.

5.1.3 Test Procedure

The tire should be prepared for testing per Section 3.

5.1.3.1 Inflation Pressure

Inflate the tire to the required pressure, set the yaw angle and apply the vertical load. Roll the tire at a constant speed of (1.0 to 2.0 in/s). Record roll distance and lateral force time histories. The tire must roll a minimum of one full revolution for accurate results. At the end of the run, lift the tire from contact, reapply the load, and return to the starting point while again recording both roll distance and lateral force.

5.1.3.2 Yaw Angle:

Runs at ±2 degrees, ±4 degrees, and ±6 degrees should be sufficient in most cases. Each positive and negative yaw angle run should be averaged together for the final curve. The positive and negative yaw angle pairs are required to account for any ply-steer effects.

5.1.4 Data Reduction

Tire relaxation behavior is described by the theoretical relationship as used in the most common reference on aircraft tire characteristics (Reference 2.1.2.1 Equation 63):

$$F_y = F_0 - A_1 e^{-x} / L_y \qquad \text{(Eq. 4)}$$

where:

F_y, = lateral force

F_0 = steady state force

A_1 = a constant depending on initial tire distortion

x = distance rolled

L_y = yawed-rolling relaxation length

The following equation may be used as an alternate to Equation 4.

$$F_y = C_\psi \psi \left(1 - e^{-x/L_y}\right) + A_1 \qquad \text{(Eq. 5)}$$

where:

C_ψ = cornering stiffness

ψ = yaw angle

The principal problem lies in generating repeatable results. Since relaxation is not measured directly, data analysis techniques can be more important than test equipment. Test machine requirements include the ability to roll the tire at a fixed yaw and vertical load while measuring the forces in the lateral direction (parallel to the axle). Minimum data acquisition would record lateral force and roll distance. Typical test data is shown in Figure 10. Output should be in a form to facilitate regression analysis.

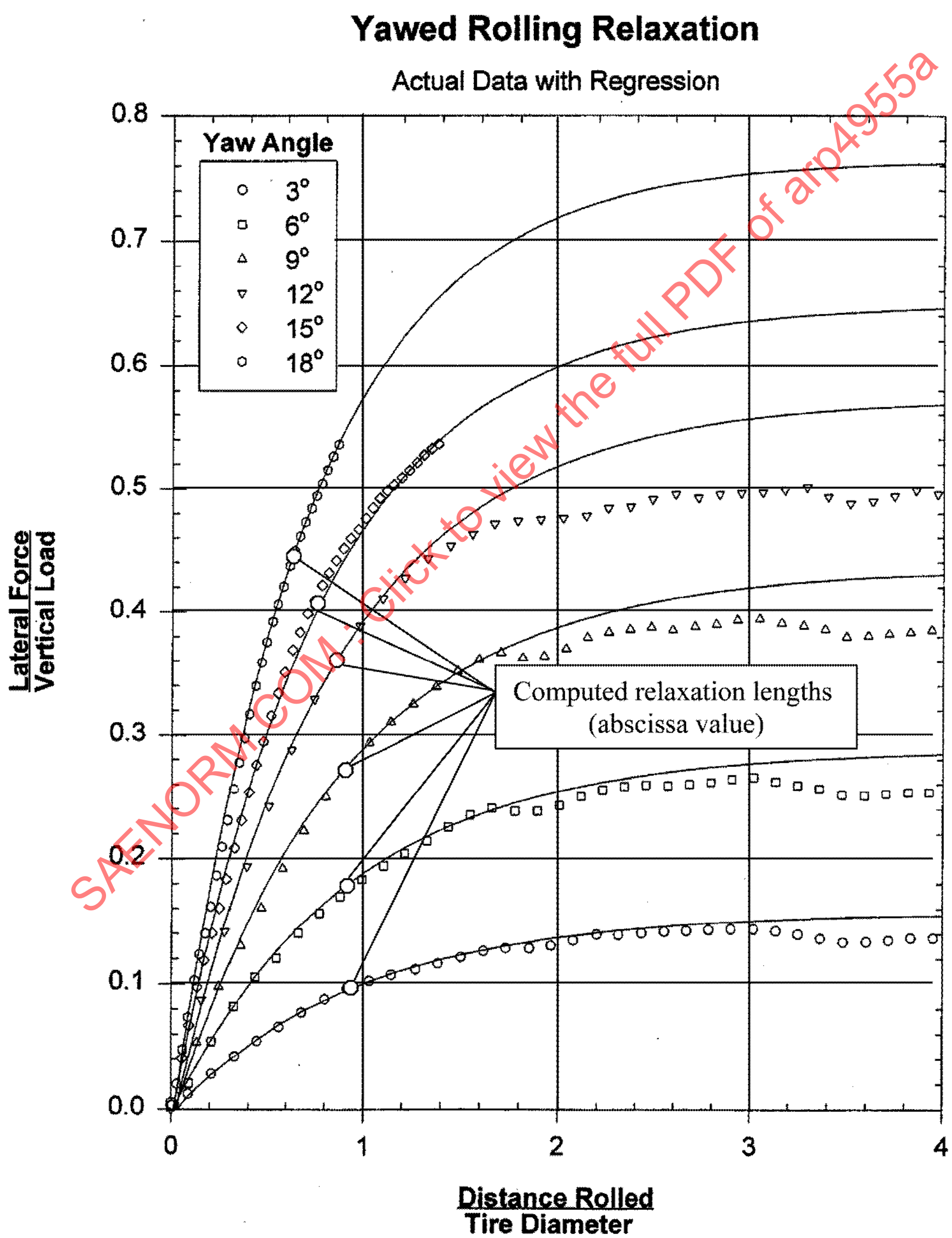

FIGURE 10 - TYPICAL TEST DATA

5.2 Unyawed-Rolling Relaxation Length

If a loaded tire is subjected to a lateral displacement, a reaction force is developed. When the tire is then rolled forward, this force decays exponentially with distance. The unyawed rolling relaxation length represents the distance which the tire must roll for the force to decline from that resulting initial displacement to 36.8% of this value. The decay function that describes this is:

$$F_y = A_2 e^{-x/L_f} \quad \text{(Eq. 6)}$$

or alternately:

$$F_y = K_1 \delta e^{-x/L_f} \quad \text{(Eq. 7)}$$

where:

L_f = unyawed rolling relaxation length

A_2 = a constant depending on the initial lateral force

K_l = lateral stiffness of the tire (slope of the line CE in Figure 5)

δ = initial prescribed lateral deflection

This function is shown in Figure 11.

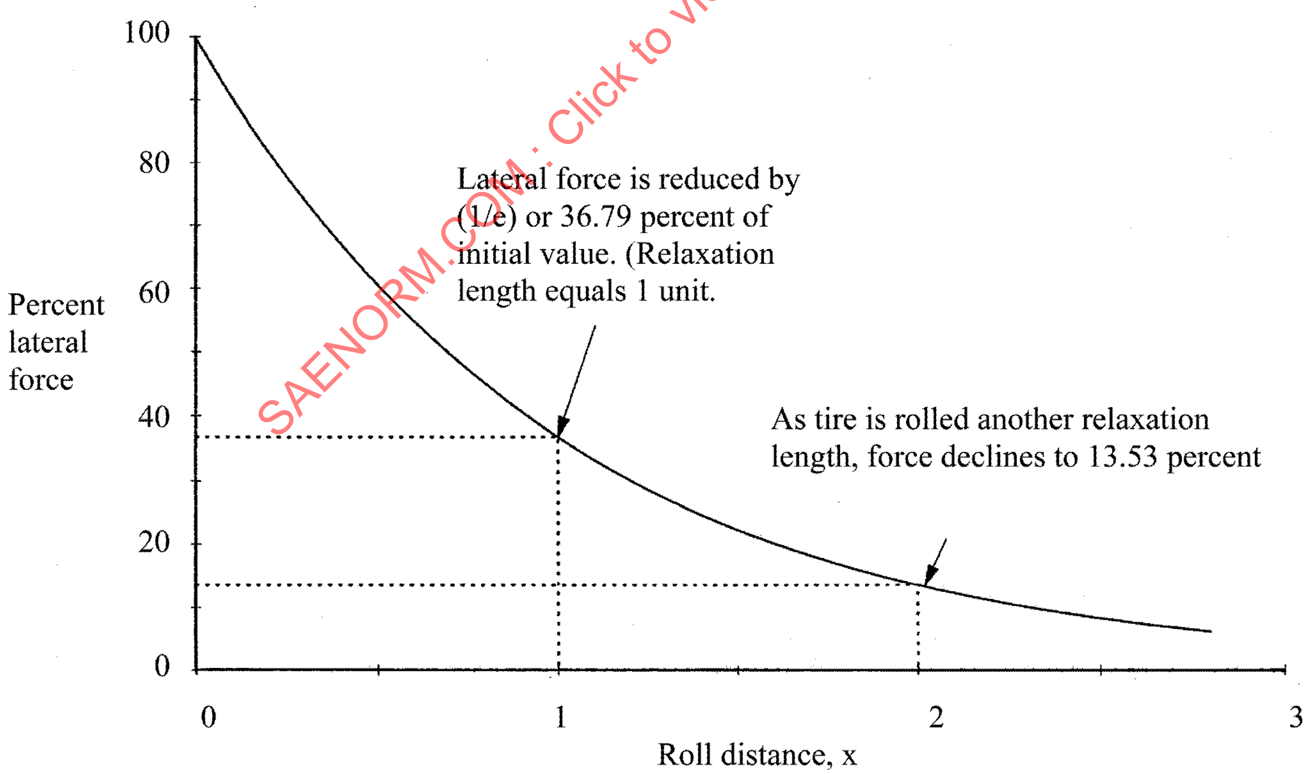

FIGURE 11 - UNYAWED ROLLING RELAXATION

The relaxation length can be seen in Figure 10 to be independent of initial displacement, or even whether slip occurs initially. If slip is observed as a discontinuity in the data, the regression should be performed over another region of the data.

5.2.1 Equipment Description

Accurate measurement of lateral force F_y as a function of roll distance and lateral displacement is critical for consistent results. The test machine must also be capable of displacing the loaded tire laterally, and then rolling the tire in a direction perpendicular to the axle.

5.2.2 Applicable Range of Measured Parameters

Relaxation length will vary with vertical deflection.

Relaxation length should be measured at several vertical deflections over the range to be characterized. This will permit accurate predictions within the range.

5.2.3 Test Procedure

The tire should be broken in per Section 3.

5.2.3.1 Define Required Displacements

The tire should be displaced as far as practicable. Should the tire begin to slip when the roll begins, the affected segment should be deleted from the regression analysis. As a guide, test equipment capable of displacing the tire a distance equal to half its section height and roll for at least one full revolution should be capable of excellent characterization of relaxation length.

5.2.3.2 Measurement

Inflate the tire to the specified test condition, apply the required vertical load, and displace the tire laterally as far as practicable. Roll the tire as far as practicable (up to three revolutions) at a constant speed of (1.0 to 2 in/s). Record roll distance and side force.

5.2.4 Data Reduction

The regression equation should be of the form:

$$F_y = C_1 + C_2 e^{\frac{-x}{L_f}} \quad \text{(Eq. 8)}$$

where:

C_1 = zero offset

C_2 = initial tire lateral force

F_y = lateral force time history

L_f = relaxation length

x = rolled distance

The variables C_1 and C_2 are measurement artifacts, needed to perform the regression but otherwise not significant.

5.3 Rolling Cornering Properties

The cornering response of an aircraft tire is characterized by a number of properties relative to the plane of the wheel including lateral force F_y perpendicular to the velocity vector or side force F_s perpendicular to the wheel plane, drag force aligned with the velocity vector F_x or with the wheel plane F_d, aligning moment M_Z and overturning moment M_X. The forces and moment developed in the footprint plane of an aircraft tire subjected to a steering input are shown in Figure 12.

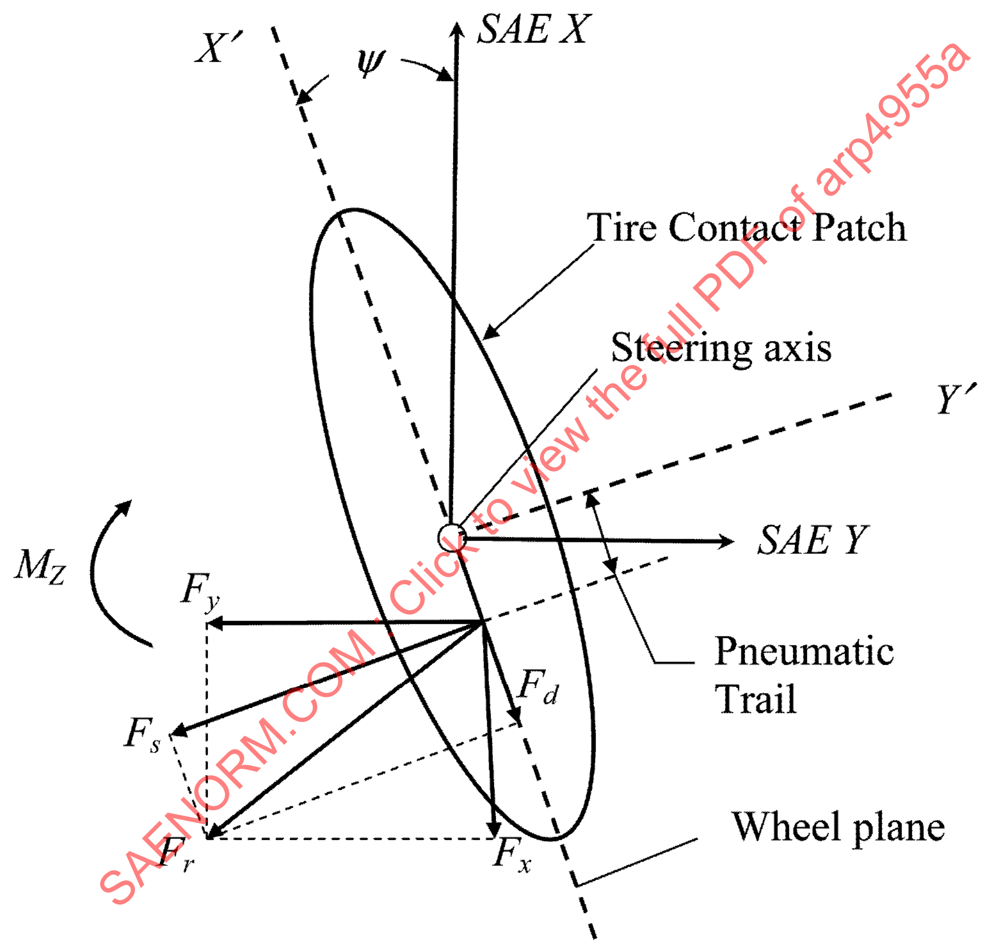

FIGURE 12 - FORCES AND MOMENT IN THE TIRE AT AXLE

In this figure the tire is rolling at a yaw angle ψ. The forces developed within the footprint include the drag force F_d parallel to the wheel plane, the side force F_S perpendicular to the wheel plane, and the resultant force F_r which is the vector sum of F_d and F_S. The aligning moment M_z is the result of the side force F_s acting through a moment arm defined as pneumatic caster in Reference 2.1.2.1 (more commonly referred to as pneumatic trail).

NOTE: Dynamometer test facilities typically provide force data as measured in the coordinate axis system of the test wheel (denoted by X' and Y' in Figure 12). Airframers and other requesting customers may require or expect force data in terms of the velocity (roadwheel) coordinate axis system (SAE X and SAE Y in Figure 12). Care should be taken that both requestor and test lab agree and understand which data are to be provided, and that those data are properly identified.

The forces developed within the vertical plane perpendicular to the wheel plane (Figure 6) are the lateral force F_S and the vertical load F_Z. The moment developed by the tire in this plane is commonly referred to as the overturning moment M_X. This overturning moment affects the load distribution between the two wheel flanges and is, therefore, an important consideration in wheel design. The overturning moment can be expressed in terms of the two forces F_S and F_Z as follows:

$$M_x = F_s h + F_z y_c' \quad \text{(Eq. 9)}$$

where:

h = axle height above the runway

y_c' = lateral center-of-pressure shift due to the applied side force

5.3.1 Equipment Description

Testing will require accurate measurement of the lateral force, drag force, vertical load, aligning torque, and overturning torque. The drag force measurement should be independent of any brake torque interaction. The instrumentation may involve multiple instrumented load beams to measure the drag force F_d and vertical load F_Z as illustrated in Figure 13. The load distribution between the two drag force beams in the figure is a measure of the aligning torque. The load distribution between the two vertical load beams is a measure of the overturning torque. Figure 13 is a schematic of an instrumentation system that has been used to obtain aircraft tire cornering characteristics.

NOTE: The equipment as shown if Figure 13 typically utilizes an axle supported on both ends and not cantilevered like an aircraft axle. Airframers and other requesting customers may require the adjustment of the setup parameters for on-aircraft axle deflection.

5.3.2 Applicable Range of Measured Parameters

The cornering characteristics of aircraft tires vary with a number of test parameters including yaw or steering angle, vertical load, brake torque, and ground speed. The cornering characteristics of aircraft tires should be measured over the expected operational range of yaw angles, vertical loads and speeds.

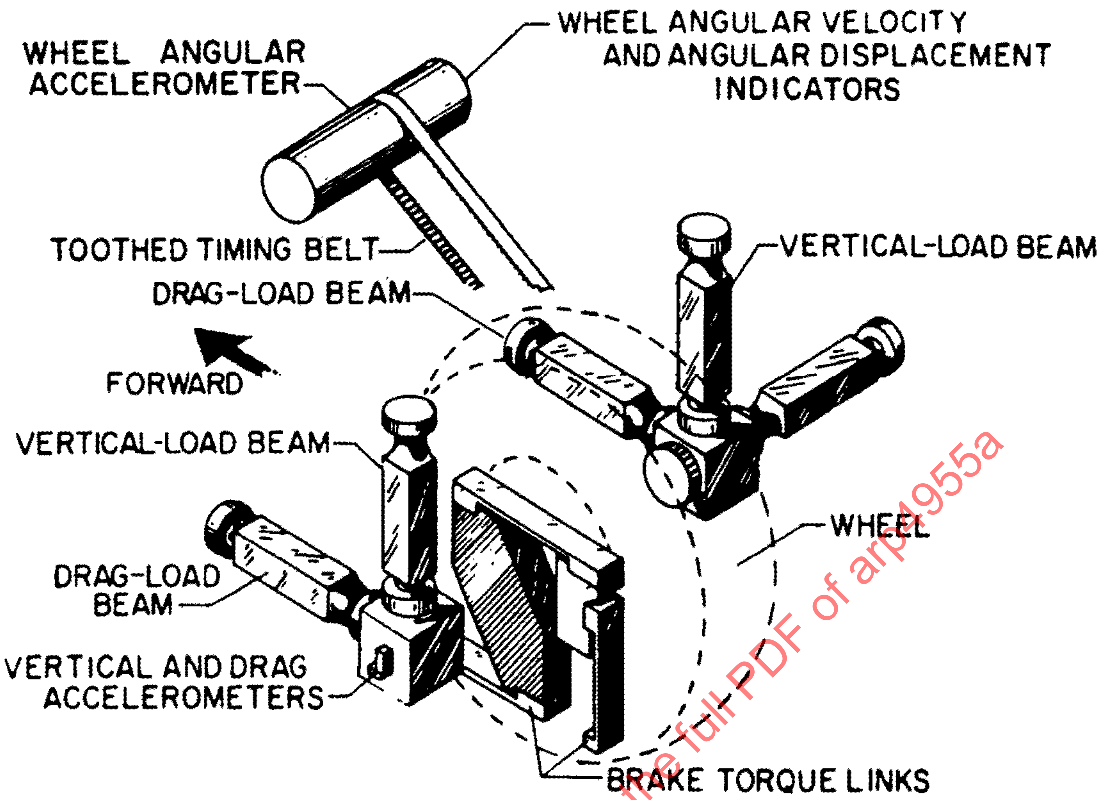

FIGURE 13 - SCHEMATIC OF INSTRUMENTED DYNAMOMETER USED TO MEASURE TIRE CORNERING CHARACTERISTICS

5.3.3 Test Procedures

The tire should be prepared for testing per Section 3.

5.3.3.1 Constant Yaw Angle Tests:

Inflate the tire to the desired inflation pressure and set the yaw angle. While rolling the tire at the desired ground speed apply the vertical load at a rate not to exceed 10% deflection per second. The range of vertical loads should cover the expected tire loading conditions. Record the side force F_S, drag force F_d, aligning moment M_z vertical load F_Z, and axle height h (optional) as time histories. The tests should be conducted over the expected operational range of yaw angles and speeds so that the tire cornering response is completely defined within the tire operational envelope.

5.3.3.2 Constant Vertical Load Tests

Inflate the tire to the desired inflation pressure and roll the tire at the desired speed and vertical load. With the tire initially in a free rolling condition apply the yaw angle at a rate not to exceed 0.3 degree/inch of travel. The range of yaw angles should cover the expected range of steering inputs. Record the side force F_S, drag force F_d, aligning moment M_z, vertical load F_Z, and axle height h (optional) as time histories. The tests should be conducted over the expected operational range of vertical loads and speeds so that the tire cornering response is completely defined within the tire operational envelope.

5.3.4 Data Reduction

Simple time history plots of the various characteristics may be adequate for some applications. However, the use of carpet plots to illustrate the functional relationships that exist between the cornering characteristics and the test parameters is the preferred method of data reduction. For example the carpet plot shown in Figure 14 represents the side-force friction coefficient μ_s, defined as the side force F_S divided by the vertical load F_Z, of the Space Shuttle orbiter nose-gear tire as a function of side force friction, vertical load and yaw angle where the ground speed is denoted by test point symbols. The figure also illustrates the use of weighted, least-square lines of constant vertical load and yaw angle to serve as interpolation aids.

For a possible alternative to the carpet plots in Figure 14 consider the following: calculate the cornering stiffness which is the side force/yaw angle and the pneumatic trail which is the aligning moment/side force.

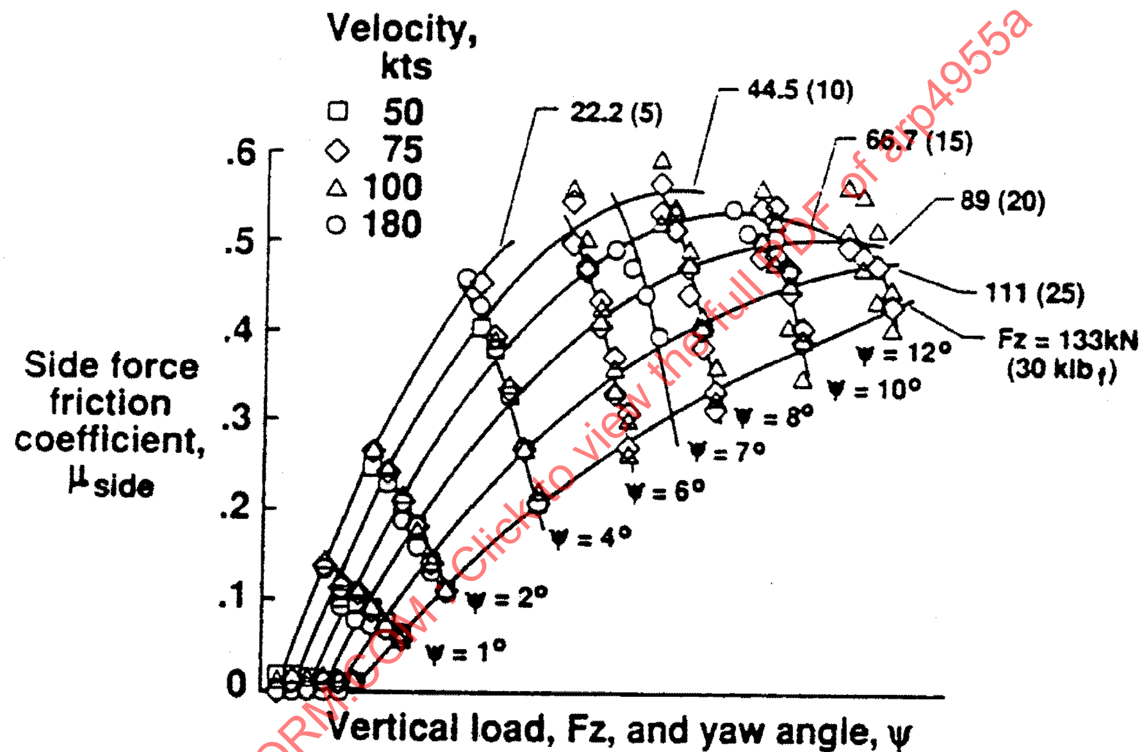

FIGURE 14 - VARIATION OF SIDE-FORCE FRICTION COEFFICIENT OF THE SPACE SHUTTLE ORBITER NOSE GEAR TIRE WITH VERTICAL LOAD AND YAW ANGLE

5.4 Rolling Radius

The effective rolling radius of a tire can be expressed as the ratio of the velocity of the wheel in the horizontal direction to its angular velocity under the conditions of free rolling with no external brake torque applied.

$$r_e = \frac{V}{\Omega} \qquad \text{(Eq. 10)}$$

where:

r_e = effective rolling radius

V = horizontal velocity of wheel

Ω = angular velocity of wheel

The rolling radius is the ratio of the deflected tire circumference to $2 * \pi$. Since this dimension is non circular, this is not equal to the height of the axle above ground.

The effective radius of a bias construction tire rolling on a flat surface can be approximated by using the following equation (Reference 2.1.2.1):

$$r_e = r - \frac{\delta}{3} \qquad \text{(Eq. 11)}$$

where:

r = tire undeflected grown radius

δ = tire deflection

The effective radius of a radial construction tire rolling on a flat surface can be approximated by using the following equation (Reference 2.1.2.5):

$$r_e = r - \frac{\delta}{5} \qquad \text{(Eq. 12)}$$

5.4.1 Free Rolling Radius

5.4.1.1 Equipment Description

Since calculation of effective rolling radius requires measurement of the angular velocity of the wheel, measurement of rolling radius shall be performed on a dynamometer which has adequate instrumentation to accurately determine the tire and drum velocities.

5.4.1.2 Applicable Range of Measured Parameters

Tire vertical load and its pressure, at which the effective rolling radius is to be measured, should be clearly specified. Critical conditions are tire rated load and rated pressure and the typical single wheel load corresponding to the pressure.

Depending on the tire construction centrifugal growth at high speeds can have a significant influence on the value of effective rolling radius. Consequently measurements should be made at a minimum of four speeds up to the rated speed of the tire. From these data points a graph of rolling radius versus speed can be plotted.

5.4.1.2.1 Tire Preparation

The tire should be prepared for testing per Section 3.