



Tire Steady-State Force and Moment

1 Introduction

Note: Nothing in this standard supercedes applicable laws and regulations.

Note: In the event of conflict between the English and domestic language, the English language shall take precedence.

1.1 Purpose. This document describes the test equipment requirements, test methodology, and data analysis for quantifying the steady-state Force and Moment (F and M) properties of a given tire to support vehicle performance simulations and the tire engineering approval process.

1.2 Applicability.

1.2.1 For all passenger cars and light truck tires.

1.2.2 Only F and M properties determined from new, unused tires are appropriate for tire design validation to Component Technical Specification (CTS) requirements.

1.2.3 Tire F and M properties for vehicle simulations may require quantifications of tires in their current state for purposes of aligning vehicle simulation results to objective vehicle test results.

1.3 Remarks.

1.3.1 The tire F and M properties are important to various vehicle simulation groups, since these tire properties will dictate to a great extent the vehicle's response to specific control inputs.

1.3.2 The F and M properties are a key element within the CTS for tires and in the validation of specific tire design to those requirements.

1.3.3 Tire F and M properties are dependent upon almost every physical characteristic of a tire including the tire structure, compounds, and tread design.

1.3.4 Tire F and M properties are also dependent upon the usage environment such as the load, inflation pressure, rim width, speed, state of wear, both ambient and tire temperatures, tire age, storage history, and usage history.

1.3.5 The quantification of tire F and M properties requires the measurement of the net resultant forces and moments from stresses within the tire footprint area. This implies the footprint dynamics on the measurement equipment must be similar to those experienced under actual vehicle operation. Therefore, a flat surface machine using a textured surface is required for the quantification of tire F and M properties.

1.3.6 Since the tire F and M properties are dependent upon many factors, the measurement equipment, surface curvature, surfaces texture, and procedures must be in substantial agreement to demonstrate the correlation of the test results.

1.3.7 This procedure involves a specific sequence of mechanical solicitations of the test tire with data collection under steady-state conditions. This procedure specifically describes the standard Ten (10) Degree Slip Angle Test. Other sequences of slip and/or camber angle solicitation of the test tire are available and may be used to generate information to meet specific data requirements. See Appendix B, Table B1.

1.3.8 General F and M tests are limited to those tests where either slip angle or camber angle independently are varied along with a range of loads. This is primarily due to limitation within the data analysis employed.

1.3.8.1 The analysis methodology described in this procedure is limited to a single dependent variable (F_y , M_z , or M_x) and two independent variables (F_z and either slip angle or camber angle).

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

March 2014

Page 1 of 24

2 References

Note: Only the latest approved standards are applicable unless otherwise specified.

2.1 External Standards/Specifications.

FMVSS 110

2.2 GM Standards/Specifications.

GMW16590

2.3 Additional References.

- Component Technical Specifications (CTS)
- Correlation Test Procedure (available through GM Tire and Wheel Systems Test Engineer)
- Equipment Maintenance Log
- European Tire and Rim Technical Organization (ETRTO) Yearbook
- F and M Test Log
- MTS Systems Corporation, Eden Prairie, Minnesota
- Rubber Manufacturer's Association Mounting Procedures
- Sourcing Documents
- The Tire and Rim Association (T and RA), Incorporated, Guidelines

3 Resources

3.1 Facilities. Not applicable.

3.2 Equipment. The equipment used to measure steady-state F and M tire properties is a MTS Flat-Trac I, or equivalent (available through MTS Systems Corporation based in Eden Prairie, Minnesota). The equipment must be properly maintained and calibrated to traceable standards.

3.2.1 The MTS Flat-Trac equipment uses a cantilevered spindle fixture upon which tire and wheel assemblies may be readily mounted. The equipment provides steady-state loading of the tire against a flat, textured surface. The equipment provides a means for steering the tire a specified amount about the Z-axis (slip angle) and about the X-axis (camber angle). A series of load cells connect the spindle to the frame of the machine.

3.2.2 The MTS Flat-Trac I machine consists of four (4) main systems which all contribute to the tire measurement system: (1) mechanical inputs, (2) roadway surface, (3) transducer system, and (4) data acquisition.

3.2.2.1 Mechanical inputs during the test include the slip angle, camber angle, and radial load which are controlled through a closed-loop feedback system. Slip and camber angles are measured using rotational transducers located at the top and to the side of the machine, respectively. The load is measured by the F_z transducer in the load cell assembly. Changes in the mechanical inputs are provided by a set of hydraulic actuators.

3.2.2.2 The roadway surface includes the mechanical devices which supports the tire during the measurement process and provides the interface through which the forces and moments are reacted.

3.2.2.2.1 The test surface consists of an abrasive material glued to a steel belt. This material is 120-grit 3M-ite. This product is used to simulate the texture of a typical road surface. In order to more closely represent the road surface, the surface macro texture is reduced through a stoning process and broken-in prior to the initial use. See Appendix D, Sections D1 thru D6, for the details regarding new surface preparation.

3.2.2.2.2 The test surface is applied to a steel belt which wraps around a pair of drums and slides over a hydrostatic water bearing located under the contact patch of the test tire. This bearing must evenly react to the vertical forces generated within the tire footprint. The bearing must be oriented parallel to the spin axis of the test spindle and perpendicular to the wheel plane.

3.2.2.2.3 The roadway control system must control the speed, direction, and tracking of the roadway.

3.2.2.3 The transducer system must measure the five forces and moments generated by the tire, as well as the slip and camber angles and the loaded radius. See Table 1.

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

March 2014

Page 2 of 24

3.2.2.4 The data acquisition system must acquire the output from the transducers, translating those outputs into digital values, and then converting those digital values into scaled engineering units.

3.2.2.4.1 The data acquisition method utilized for this procedure is described as revolution averaged data acquisition. This method uses a spindle encoder to clock the data acquisition at a minimum rate of 256 pulses per tire revolution. A minimum of one full revolution of data is collected and averaged to obtain a single value for each channel.

3.2.3 The full scale capabilities of the MTS Flat-Trac I equipment are given in Table 1.

Table 1: Full Scale Capacities

Parameter	SAE Symbol	Full Scale	Units
Longitudinal Force	F_x	1000	N
Lateral Force	F_y	14 000	N
Radial Load	F_z	24 000	N
Overturning Moment	M_x	10 000	N·m
Aligning Moment	M_z	1000	N·m
Loaded Radius	R_L	450	mm
Slip Angle	α	± 15	degrees
Camber Angle	γ	± 10	degrees
Speed	V_s	$\pm 3.6, \pm 7.2$	km/h

3.3 Test Vehicle/Test Piece.

3.3.1 Test Specimen. The test tire must be free of all tags, tape, stones, or any other foreign material in the tread area.

3.3.2 Test Wheel. The wheel must be selected properly to facilitate correct test results. The following should be considered when selecting the proper test wheel.

3.3.2.1 The wheel width must match that requested on the test request.

3.3.2.2 The wheel must have the proper rim flange contour for the test tire as required by the Tire and Rim Association (T and RA) or equivalent.

3.3.2.3 A spindle adaptor must exist to interface with the wheel bolt circle and pilot area to facilitate the mounting of the wheel on the machine.

3.3.2.4 A spacer set must exist to make the wheel plane coincident with the center of the machine's coordinate system. This spacer set compensates for the offset of the wheel.

3.3.3 Test Surface. The roadway surface must be free of foreign material including, but not limited to, oils, rubber dust, or other deposits from previous usage. See Appendix E, Sections E1 thru E5.

3.3.4 Sample Size. Consideration must be given to the number of tires to be tested, or sample size, for a specific purpose.

3.3.4.1 A three (3) tire sample is recommended for testing to determine the F and M properties for a specific tire construction. All tires within a sample are to be tested consecutively.

3.3.4.2 A two (2) tire sample, whose F and M data is in substantial agreement, is often considered adequate for simulation purposes.

3.3.4.3 A three (3) tire sample is required when the data is for design validation to CTS requirements.

3.3.5 Multiple Tests per Specimen. Conducting multiple tests on a single specimen, or retesting, is not recommended. If multiple tests must be run on a single specimen, the following must be carefully considered when validating the test results.

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

March 2014

Page 3 of 24

3.3.5.1 The test specimen must be allowed to return to thermal equilibrium with the ambient environment of the test room. Generally, 3 h between tests is sufficient. This will allow the tire to begin the next test as close as possible from a structural perspective, increasing test repeatability.

3.3.5.2 F and M testing involving slip angles are destructive tests. Each successive test will begin with the tire in a different state. Tread wear is often not uniform across the tire, therefore, both tread stiffness and contact stress distribution within the footprint area evolves with each successive test.

3.3.5.3 Carefully consider the purpose of the test results, selecting the least destructive test possible to achieve that purpose. The destructiveness of a given test is associated first with the maximum slip angle within the test and, to a lesser extent, with the load applied to the test tire.

3.4 Test Time.

Calendar time: 1 day

Test hours: 1 hour

Coordination hours: 0.5 hours

3.5 Test Required Information.

3.5.1 This information regarding the tire must be provided in order to facilitate the test.

- Construction number
- Tire size
- Service description
- Supplier (manufacturer)
- Load rating

3.5.2 This information related to the desired test conditions must also be specified.

- Rim width
- Load
- Inflation pressure

3.5.3 Providing this information can be useful in identifying the data, but is not required for facilitating the physical testing.

- Tire type code
- Brand name (e.g., **Eagle RS-A**)
- Sidewall type (e.g., **Raised White Letters**)
- Program designation

3.6 Personnel/Skills.

3.6.1 Test operators must be trained in the safe operation of the measurement equipment. The measurement equipment, by necessity, involves moving parts and loading mechanisms which must be understood and operated using proper safety precautions.

3.6.2 Operators must be trained in the selection of test components and fixtures to facilitate the proper testing of the tires.

3.6.3 Operators must be trained to observe, and correct when necessary, the test surface condition. The surface condition and contamination level directly impact the quality of the test results.

4 Procedure

4.1 Preparation.

4.1.1 Thermally stabilize the test tire by storing in an area with an ambient temperature within 5 °C of the test machine environment for at least 24 h prior to testing.

4.1.2 Mount the test tire on the test wheel.

4.1.2.1 Follow approved mounting procedures, such as those published by the Rubber Manufacturer's Association, when mounting the test tire onto test wheels.

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

March 2014

Page 4 of 24

4.1.2.2 Inspect the tire bead and the bead seat of the wheel to ensure this interface is free of damage, defects, and foreign material. Clean or replace test pieces as necessary.

4.1.2.3 Use only a thin film of an approved mounting lubricant to facilitate proper tire mounting and bead seating. Excessive mounting lubricant can cause slippage at the tire and rim interface during testing.

4.1.2.4 Inspect the bead area of the mounted tire and wheel assembly to ensure the tire bead is firmly seated on the wheel.

4.1.3 Inflate the tire and wheel assembly 30 kPa above the required test inflation pressure and allow the tire to stabilize at room temperature.

4.1.3.1 If this is the first mounting of the test tire within the previous 24 h, then allow the assembly to stabilize for at least 3 h.

4.1.3.2 If the tire was previously mounted and inflated within the last 24 h period and is now being re-mounted, then the assembly needs to stabilize only for a period of five (5) minutes which is approximately the amount of time needed to mount it onto the test machine.

4.2 Conditions.

4.2.1 Environmental Conditions. The ambient temperature in the room where the measurement equipment is operating shall be controlled to $21\text{ }^{\circ}\text{C} \pm 3\text{ }^{\circ}\text{C}$ to minimize the thermal gradients within the test equipment and instrumentation.

4.2.2 Test Conditions. Deviations from the requirements of this standard shall have been agreed upon. Such requirements shall be specified on component drawings, test certificates, reports, etc.

4.2.2.1 The standard test speed is 3.6 km/h.

4.2.2.2 If load and inflation pressure conditions are not specifically provided, use the Standard Test Conditions in Appendix A, Table A1.

4.2.3 Test Sequencing. The test sequences of slip and/or camber angles are documented in Appendix B, Table B1.

4.3 Instructions.

4.3.1 Mount Tire. Mount the tire and wheel assembly onto the test machine spindle using the proper adapter and spacers.

4.3.2 Set Inflation Pressure. Set the tire and wheel assembly inflation pressure to the test inflation pressure.

4.3.3 Perform Break-In. Perform a break-in procedure unless the tire has been tested within the last 30 minutes.

4.3.3.1 The break-in procedure is intended to relax residual, transient stresses within the tire due to packaging, storage conditions, or other causes by exercising the structural elements of the tire.

4.3.3.2 Set the roadway speed to 7.2 km/h.

4.3.3.3 Set the load to 80% of the test load.

4.3.3.4 Sequence through each of the eight slip angles, dwelling at each for approximately 30 s: 0.0 degrees, -1.0 degrees, +1.0 degrees, +2.0 degrees, -2.0 degrees, -4.0 degrees, +4.0 degrees, and 0.0 degrees.

4.3.3.5 Set the load at 2% of the tire's maximum load capacity and then ramp load to 160% of the tire's maximum load capacity at a rate of 444 N/s.

4.3.3.6 Repeat the preceding step for each of the eight slip angles: 0.0 degrees, -1.0 degrees, +1.0 degrees, +2.0 degrees, -2.0 degrees, -4.0 degrees, +4.0 degrees, and 0.0 degrees.

4.3.3.7 Remove the load from the test tire.

4.3.3.8 Stop the roadway if the inflation pressure is adjusted by the operator.

4.3.4 Check Inflation Pressure. Check the tire and wheel assembly inflation pressure and reset to the test inflation pressure.

4.3.5 Inspect Test Surface. Inspect the test surface on the machine and remove rubber dust and debris as necessary.

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

March 2014

Page 5 of 24

4.3.6 Zero Transducers. Collect tare readings from all measurement transducers, taking into consideration the range of slip angle and camber angles which will be achieved during the test sequence.

4.3.7. Set Roadway Direction. Set the roadway direction for a clockwise rotation of the test assembly.

4.3.8 Set Test Speed. Set the roadway speed to the test speed.

4.3.9 Apply Skim Load. Set the load to about 500 N.

4.3.10 Set Slip and Camber Angle. The first slip and camber angle in the test sequence will be zero degrees.

4.3.11 Set Load. The first test load will be 20% of the test load.

4.3.12 Stabilize Conditions. Allow the machine control system to achieve the commanded set points and allow the tire and wheel assembly to stabilize for one complete revolution.

4.3.13 Collect Data. Collect the force and moment data for at least one complete revolution of the test assembly. Spindle clocked data acquisition is preferred with at least 256 equidistant sampling locations per revolution.

4.3.14 Complete Load Sequence. Repeat 4.3.11 thru 4.3.13 for all remaining load conditions up to the 160% the test load (see Appendix B, Table B1, Test Loads).

4.3.15 Apply Skim Load. Return to a skim load of about 500 N.

4.3.16 Complete Test Sequence. Repeat 4.3.10 thru 4.3.15 for all of the remaining slip or camber angles for the test executed in Appendix B, Table B1.

4.3.17 Remove Load. Unload the test tire.

4.3.18 Stop the Roadway.

4.3.19 Dismount the Tire. Remove the tire and wheel assembly from the machine and dispose of test pieces per disposition instructions.

5 Data

5.1 Calculations.

5.1.1 The raw data analysis detailed in this section, assumes the data is either acquired or has been preprocessed such that the statements in 5.1.1.1 thru 5.1.1.4 regarding the raw data, or machine generated test results, are true.

5.1.1.1 Data is represented in metric units with appropriate tare measurements subtracted and gain factors applied.

5.1.1.2 Data sign conventions are consistent with the SAE International coordinate system.

5.1.1.3 The data was collected using the data acquisition method described in the instructions section.

5.1.1.4 Data was collected while the input conditions to the tire were held constant, resulting in data which can be considered steady-state.

5.1.2 The raw data is used to generate three dimensional surfaces, or functions, with a cubic relationship to both independent variables. The mathematical form is a bi-cubic spline.

5.1.2.1 The applied load, F_z , and the slip angle, α , are considered the independent variables for each surface.

5.1.2.2 Four (4) surfaces are created to represent the raw data from the lateral force, F_y , overturning moment, M_x , aligning moment, M_z , and the loaded radius, R_L measurements.

5.1.2.3 The surfaces are all considered to be independent of each other.

5.1.2.4 The form of the resulting function can be demonstrated using the F_y function as an example,

$$F_y = f(F_z, \alpha)$$

or

$$\begin{aligned} F_y = & [C_{1,1} + C_{1,2}\alpha^1 + C_{1,3}\alpha^2 + C_{1,4}\alpha^3] \\ & + [C_{2,1} + C_{2,2}\alpha^1 + C_{2,3}\alpha^2 + C_{2,4}\alpha^3]F_z \\ & + [C_{3,1} + C_{3,2}\alpha^1 + C_{3,3}\alpha^2 + C_{3,4}\alpha^3]F_z^2 \\ & + [C_{4,1} + C_{4,2}\alpha^1 + C_{4,3}\alpha^2 + C_{4,4}\alpha^3]F_z^3 \end{aligned}$$

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

5.1.2.5 These 16 coefficients, $C_{i,j}$, are necessary to define one bi-cubic patch. However, the nature of the surfaces is such that a series of bi-cubic patches are needed to accurately represent the physical data.

5.1.2.5.1 This is done by dividing the independent axes into a series of zones. The values of the boundaries of these zones are commonly known as the joints. The following example is for the standard ten (10) degree slip angle test. See Appendix C, Table C1 for the joint locations of other test sequences.

5.1.2.5.2 The slip angle, α (measured in degrees), axis is divided into seven (7) zones:

$$\begin{aligned} -10.0 &\leq \alpha \leq -7.0 \\ -7.0 &\leq \alpha \leq -4.0 \\ -4.0 &\leq \alpha \leq -1.5 \\ -1.5 &\leq \alpha \leq +1.5 \\ +1.5 &\leq \alpha \leq +4.0 \\ +4.0 &\leq \alpha \leq +7.0 \\ +7.0 &\leq \alpha \leq +10.0 \end{aligned}$$

5.1.2.5.3 The load, F_z , axis is divided into two zones, based on a percentage of the test load:

$$\begin{aligned} 0\% &< F_z \leq 70\% \\ 70\% &< F_z \leq 165\% \end{aligned}$$

5.1.2.5.4 The intersection of these zones will form 7 cells $\times$ 2 cells, or 14 cells. Each piece of captured data will fall into one of these cells. There will be one bi-cubic surface patch, or set of 16 coefficients, for each cell, and the patch will fit only the data within the boundaries of that cell.

5.1.2.5.5 Since each patch is located next to another patch, boundary conditions are also imposed at the joint locations. It is required the values of the neighboring patches be equal and the partial derivatives continuous at the joint locations. The following illustration shows where $F_{Y,1}$ and $F_{Y,2}$ are neighboring lateral force surfaces and the values of the slip angle and load represent the joint between the two surfaces,

$$\begin{aligned} F_{Y,1} &= f(F_z, \alpha), \\ F_{Y,2} &= f(F_z, \alpha), \\ X &= \text{Load}, \\ \text{and} \\ Y &= \text{Slip Angle} \end{aligned}$$

Then,

$$F_{Y,1}(X, Y) = F_{Y,2}(X, Y)$$

and

$$\frac{d}{d\alpha} F_{Y,1}(X, Y) = \frac{d}{d\alpha} F_{Y,2}(X, Y)$$

and

$$\frac{d}{dF_z} F_{Y,1}(X, Y) = \frac{d}{dF_z} F_{Y,2}(X, Y)$$

5.1.2.5.6 Variations of the preceding bi-cubic spline method would be the use of different joints or, in the case of a wider slip angle range, the addition of more joints. In the case of very small angle and load variations, it

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

March 2014

Page 7 of 24

may be desirable to fit only one patch to the entire data set. The specifics of optional analyses are largely left to the engineer to determine.

5.1.3 Reflected Data.

5.1.3.1 The surfaces generated from the raw data may be reflected during the analysis. The standard analysis methodology will generate both reflected and un-reflected surfaces, however, only the reflected data is stored in the database.

5.1.3.1.1 Reflecting the data averages the measured raw data such that, at a given load, the data measured at a positive slip angle is equal and opposite to the data measured at the following negative slip angle using the following F_Y function as an example.

$$F_Y(F_Z, \alpha) = -F_Y(F_Z, -\alpha)$$

5.1.3.1.2 Another effect of reflecting the data is the functions are equal to zero at zero slip angle using the following F_Y function as an example.

$$F_Y(F_Z, \alpha = 0) = 0$$

5.1.3.1.3 The surfaces being equal to zero at zero slip angle is desirable when calculating the F, G, and H functions of a tire since the methods of calculation assume the lateral force surface is perfectly reflected.

5.1.3.1.4 Reflected data is preferentially used to represent the characteristics of a given tire design instead of the individual tire in most instances.

5.1.3.2 Un-reflected data is used when the characteristics of a specific tire are needed. Only un-reflected data should be used when analyzing the on-center characteristics of a given tire.

5.1.4 The reflected lateral force surface generated in 5.1.3 is further analyzed to generate the F, G, and H functions.

5.1.4.1 The F function is the F_Y function normalized by F_Z :

$$F(F_Z, \alpha) = \frac{F_Y(F_Z, \alpha)}{F_Z}$$

5.1.4.1.1 The cornering coefficient (CC), a specific application of the F function, can be determined at any F_Z and always at a slip angle of one degree.

$$CC(F_Z) = |F(F_Z, \alpha = 1)|$$

5.1.4.2 The G function, Load Transfer Sensitivity, is a measure of the loss in total lateral force generated by a pair of tires, operating at some given slip angle, due to lateral load transfer. The G function is typically evaluated at a slip angle of four degrees, but can be evaluated at any slip angle.

$$G(\alpha) = \frac{[F_Y(P, \alpha) - \frac{1}{2}(F_Y(0.4P, \alpha) + F_Y(1.6P, \alpha))][P]}{(0.6P)^2}$$

Where $P = 100\%$ Tire's Load Capacity

5.1.4.3 The H function is the Load Sensitivity function and is the slope of F_Y with respect to F_Z between 80% and 100% of the tire's load capacity. The H function is typically evaluated at a slip angle of one degree, but can be evaluated at any slip angle.

$$H(\alpha) = \frac{F_Y(P, \alpha) - F_Y(0.8P, \alpha)}{0.2P}$$

Where $P = 100\%$ Tire's Load Capacity

5.1.5 The reflected aligning moment surface, generated in a manner similar to the preceding F_Y surface, is further analyzed to generate the AT function.

GM Confidential

© Copyright 2014 General Motors Company All Rights Reserved

March 2014

Page 8 of 24