SAE International	SURFACE VEHICLE RECOMMENDED PRACTICE	J2731	ISSUED NOV2006
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Low Speed Enveloping Test with Perpendicular and Inclined Cleats

RATIONALE

This Recommended Practice was developed as part of a set of Recommended Practices intended to allow modelers to determine the parameters required by any of the common tire models for calculating spindle loads given the road surface profile. The Recommended Practices provide the necessary data from a single set of experimental results, thus, eliminating duplicate testing.

1. SCOPE

This SAE Recommended Practice describes a test method for measuring the forces and moments generated at a spindle when a tire rolls over a rectangular obstacle, cleat, at very low speed. The cleat used in a particular test condition is configured with its crest either perpendicular, 90°, to the path of the tire or optionally with its crest inclined at an angle to the path of the tire. The carriage to which the spindle is attached is rigidly constrained in position during each test condition so as to provide a good approximation to fixed loaded radius operation. The method discussed in this document provides cleat envelopment force and moment and tire angular position histories as functions of distance traveled. These histories are essentially free from variations due to tire non-uniformities. The method applies to any size tire so long as the equipment is properly scaled to conduct the measurements for the intended test tire. The data are suitable for use in determining parameters for road load models and for comparative evaluations of the measured properties in research and development.

NOTE: Herein, road load models are models for predicting forces applied to the vehicle spindles during operation over irregular surfaces, paved or otherwise. Within the context of this document, forces applied to the road or terrain surface are not considered.

2. REFERENCES

2.1 Applicable Publications

The following publications form part of the specification to the extent specified herein. Unless otherwise indicated the latest revisions of all publications shall apply.

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2.1.1 SAE Publications

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

SAE J2047 Tire Performance Technology

SAE J2429 Free-Rolling Cornering Test for Truck and Bus Tires

SAE J2710 Modal Testing and Identification of Lower Order Tire Natural Frequencies of Radial Tires

SAE J2730 Dynamic Cleat Test with Perpendicular and Inclined Cleats

SAE 770870 The Effect of Tire Break-in on Force and Moment Properties, K. D. Marshall, R. L. Phelps, M. G. Pottinger, and W. Pelz, 1977

SAE 810066 The Effect of Aging on Force and Moment Properties of Radial Tires, M. G. Pottinger and K. D. Marshall, 1981

2.1.2 Rubber Manufacturers Association Publication

Available from Rubber Manufacturers Association, 1400 K Street, NW, Suite 900, Washington, DC 20005, Tel: 202-682-4800, www.rma.org.

OSHA Standard 1910.177 Servicing Multi-piece and Single Piece Rim Wheels (Available in wall chart form as #TTMP—7/95)

2.1.3 ISO Publication

Available from ANSI, 25 West 43rd Street, New York, NY 10036-8002, Tel: 212-642-4900, www.ansi.org.

ISO Standard 17025 General Requirements for the Competence of Testing and Calibration Laboratories

3. DEFINITIONS

The definitions that follow are of special meaning in this document and are either not contained in other Recommended Practices or are worded somewhat differently in this practice.

3.1 The Parallel Axis Tire Coordinate System

This system is defined in SAE J2710 and extended in SAE J2730 to allow tire rotation. For axes definitions and associated geometry, please see SAE J2730.

3.2 The Tire Forces and Moments

This set of spindle centered forces and moments is fully defined in SAE J2730.

3.3 Test

A Test is execution of the procedure described in this document one time on one tire at a single set of conditions.

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3.4 Test Program

A Test Program is a designed experiment involving a set of the tests described in this practice.[1]

4. NOMENCLATURE

Table 1 lists the symbols used in this document. For further information on items not in Section 4 of this practice please see SAE J2047.

TABLE 1 - SYMBOLS DEFINED

Symbol	Defined Term
D	Distance Traveled
$F_{X''}$	Parallel System Longitudinal Force
$F_{Y''}$	Parallel System Lateral Force
$F_{Z''}$	Parallel System Normal Force
Φ	Angular Displacement of Tire
$M_{X''}$	Parallel System Overturning Moment
$M_{Z''}$	Parallel System Aligning Moment
R_l	Tire Loaded Radius
R_{lmax}	Maximum R_l Expected During Test Machine Use
V	Test Velocity

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5. LABORATORY QUALITY SYSTEM REQUIREMENT

The laboratory performing the procedures specified in this document shall have a quality system either conforming to ISO 17025 or which can be shown to be functionally equivalent to ISO 17025. The elements of such a system are assumed below and are not, therefore, specifically called out within this practice.

6. APPARATUS

The required apparatus consists of a test machine with a test surface (round or flat bed) capable of rolling test tires over at least a quarter revolution prior to cleat envelopment, as defined in the test conditions, Section 10.4. It is preferable that the apparatus allow at least a full tire revolution before cleat envelopment starts. This would allow the relaxation phenomena to become complete.

The test surface shall allow mounting of rectangular cleats, one at a time, as specified in this practice. The machine shall have an instrumented spindle capable of measuring three forces ($F_{X''}$, $F_{Y''}$, and $F_{Z''}$) and two moments ($M_{X''}$ and $M_{Z''}$) developed during tire envelopment of the cleat. Additionally, the relative displacement of the spindle with respect to the test surface in the X"-Axis direction, D, and the tire angular displacement, Φ, about the spindle shall be measured during envelopment using absolute encoders. The speed of travel during envelopment does not have to be constant due to the angular displacement measurements that are taken. Figure 1 is a schematic of both common machine types: a round test surface (drum) and a plank. Appropriate data acquisition equipment is considered to be part of the apparatus. The space housing the loading machine is also considered to be part of the apparatus.

[1] There are many experimental possibilities: repeated tests of the same tire, tests of the same tire under multiple test conditions, tests of tires with different specifications (design details), application of this test as part of a series of different tests, etc.

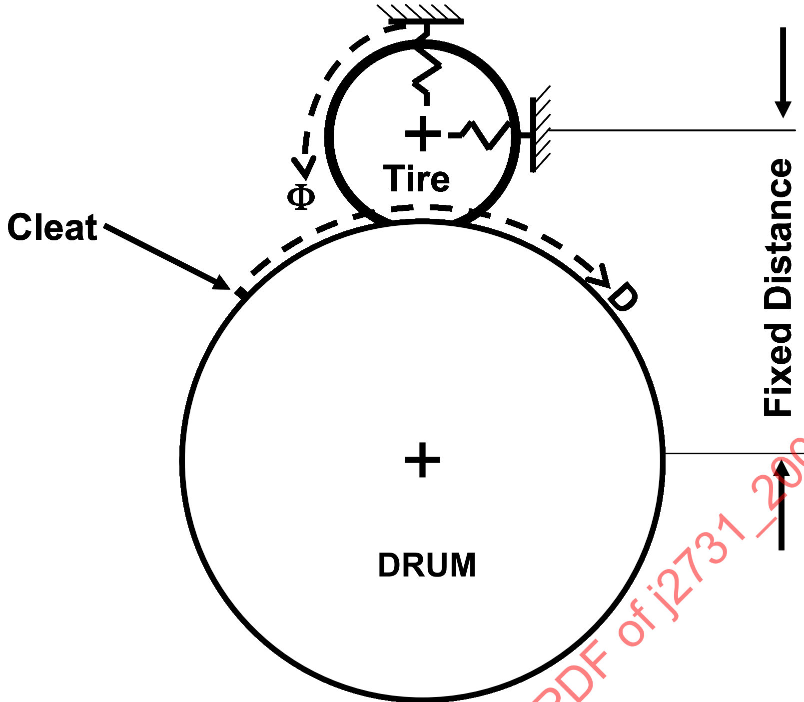

FIGURE 1A - ROUND TEST SURFACE OR DRUM MACHINE

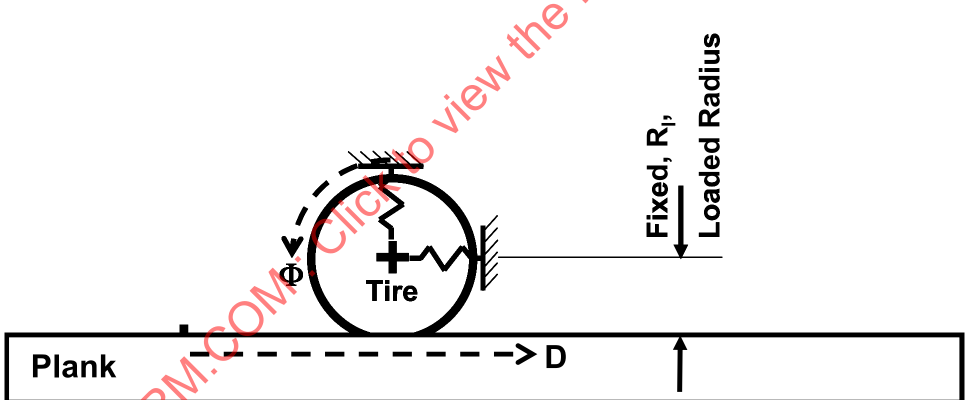

FIGURE 1B - PLANK OR FLAT SURFACE

FIGURE 1 - TEST MACHINE SCHEMATICS

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6.1 Environmental Vibration and Isolation

Cleat envelopment generates significant forces. The instrumented spindle will respond to force signals regardless of whether they reach it directly from the tire/wheel system, as is desired, or, as environmental noise, from a source in the laboratory environment through the floor and then the machine frame.

The machine's planned environment should be tested for significant structure borne vibration arising from the laboratory environment prior to installation.[2] If the vibration found is insignificant from the standpoint of this document, the machine can be mounted on a normal foundation. If significant environmentally associated vibrations are discovered, which will affect results, either follow the mitigation practices described in SAE J2730 or filter the data suitably so as to suppress spurious results due to environmental vibration.

[2] Significance is a judgment that should be made by a competent expert in machine isolation.

6.2 Loading System

The loading system shall maintain the tire at a slip angle of 0° ± 0.05° and an inclination angle of 0° ± 0.05°, common machine specifications when this document was drafted. The system shall be capable of loading the tire to at least twice the test requester specified 100% load. It shall be capable of loading the tire to an average normal force accurate to within ± 1.0% of the test machine's full-scale normal force range when no cleat is mounted and to an average loaded radius accurate to within ± 0.5 mm either with or without a cleat mounted.[3] Loading shall be possible with the test surface either static or rolling.

The loading system must be stiff enough to assure an essentially constant distance between spindle and test surface during the tire envelopment process.

So long as the machine's structural design is adequate, it is not important whether the machine is designed such that the Z"—axis is directed horizontally or vertically.

6.3 Measuring System

6.3.1 Instrumented Spindle

The spindle shall be capable of measuring three forces ($F_{X''}$, $F_{Y''}$, and $F_{Z''}$) and two moments ($M_{X''}$ and $M_{Z''}$). The output shall be corrected for load cell interaction by a matrix method conceptually equivalent to that discussed in SAE J2429.

The capacities recommended in this section are best estimates at the time this document was prepared, but are not known to be correct based on experimental evidence.

Force and moment measurements shall be accurate to ± 0.5% of each load cell's maximum capacity.

The load cell capacities given in Table 2 are believed to be adequate, but are best estimates. The loaded radius needs to be set so that the maximum vertical force is not exceeded when the tire envelops the cleat.

NOTE: A rotating wheel force transducer may be used in place of an instrumented spindle. If this is done, verify that the apparent vertical stiffness of the transducer is constant independent of its angular orientation with respect to the center of tire contact.

TABLE 2 - MINIMUM LOAD CELL CAPACITIES BASED ON FORCE AND MOMENT

Force or Moment	Load Cell Capacity
Longitudinal Force	-(Maximum 100% Tire Load[4]) ≤ $F_{X''}$ ≤ (Maximum 100% Tire Load)
Lateral Force	-(Maximum 100% Tire Load) ≤ $F_{Y''}$ ≤ (Maximum 100% Tire Load)
Normal Force	-(300% Maximum Tire Load) ≤ $F_{Z''}$ ≤ 0
Overturning Moment	-$F_{Y''}$ Capacity times R_{lmax} ≤ $M_{X''}$ ≤ $F_{Y''}$ Capacity times R_{lmax}
Aligning Moment	-$F_{Y''}$ Capacity times R_{lmax} ≤ $M_{Z''}$ ≤ $F_{Y''}$ Capacity times R_{lmax}

NOTE: By way of example, assume that the machine in question was designed to test tires with 100% loads up to 9000 N with a maximum loaded radius in test of 0.4 m. That would mean that the load cell capacities would need to be as follows.

[3] Due to tire non-uniformity, the normal force and loaded radius vary with tire angular position. Thus, when the tire is rolling the best solution is to set the tire normal force or loaded radius to a value most correspondent to its average value during a tire rotation.

[4] The Maximum 100% Tire Load is the 100% load for the largest load capacity tire the machine is designed to test.

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TABLE 3 - DESIGN LOAD CELL CAPACITY EXAMPLE

Force or Moment	Load Cell Capacity
Longitudinal Force	$-9{,}000N \le F_{x''} \le 9{,}000N$
Lateral Force	$-9{,}000N \le F_{Y''} \le 9{,}000N$
Normal Force	$-27{,}000N \le F_{Z''} \le 0$
Overturning Moment	$-3{,}600N\text{-}m \le M_{x''} \le 3{,}600N\text{-}m$
Aligning Moment	$-3{,}600N\text{-}m \le M_{Z''} \le 3{,}600N\text{-}m$

6.3.2 Loaded Radius Instrumentation

The system shall measure loaded radius over a range from at least 0.4 times the nominal bead seat diameter of the smallest wheel that is expected to be mounted up to 1.2 times the unloaded crown radius of the largest tire expected to be tested. The measurement shall be accurate within ± 0.5 mm.

6.3.3 Distance Traveled Instrumentation

The measurement system shall determine distance traveled by the tire by measuring test surface position with a resolution of 1 mm or better. The distance traveled measurement shall drive data acquistion in Section 6.4.

6.3.4 Wheel Angular Displacement Instrumentation

An absolute encoder system shall monitor tire angular position at 0.10° increments of rotation per count or better.[5]

6.4 Data Acquisition

Test data for all channels shall be acquired at a rate corresponding to the resolution in traveled distance, which is defined in Section 6.3.3. Data shall be simultaneously sampled and held at each sample of the test surface position. Data acquisition shall begin at least 50 mm before the test cleat first encounters the tire and shall end at least 50 mm after the cleat has passed out of contact with the tire. The system shall feature anti-aliasing filters applicable to the analog signals such as load cells with corner frequencies set to less than 25% of the estimated sampling frequency.[6]

Alternatively, the data could be time sampled at a frequency sufficiently large to insure approximately the same spatial resolution provided by the encoder triggered method of data acquisition. For example, sampling at 300 Hz would be sufficient at a 1 km/hr bed speed. In time sampled data acquisition the test surface encoder reading becomes one of the sampled data channels.

6.5 Test Surface

The test surface shall be stiff enough that it may be assumed rigid for the purposes of this experiment and will provide a good foundation for cleat attachment. The surface curvature shall be at most 1.176 m^{-1} (drum diameter 1.7 m or more, or flat bed).

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[5] A 4096-count encoder meets this requirement. By way of example, this would divide the circumference of common Truck Bus Radials and all smaller tires into circumferential increments of less than 1 mm per count.

[6] While the test speed does not have to be precise, see Section 6, it should be reasonably well determined to facilitate filter selection.

6.6 Test Cleats

The purpose of the cleats, which are sized so that they encounter the entire tread width, is to excite a nonlinear response due to large quasi-static tire deformation occurring during enveloping. These large deformations of the tire are comparable to those encountered during travel on a rough surface. Two cleats are suggested for passenger and light truck tires: 15 mm X 15 mm[7] and 25 mm X 25 mm. Each cleat has a square cross section with a 2 mm by 45° bevel on the corners transverse to the test roadway, Figure 2. These cleat cross sections may not be adequate for users who wish to test larger tires. They will typically need cleats with a larger cross section.

NOTE: The Task Force, which is a temporary entity organized by the Vehicle Dynamics Standards Committee, does not have evidence as to a proper cleat size for TBR, farm or OTR tires, but its engineering judgment is to begin experiments to determine a proper cleat on the basis given in the note at the end of this section. If those developing cleats for TBR, farm and OTR tires will share their results with the Vehicle Dynamics Standards Committee, the next revision of this document will contain specific recommendations for cleat sizing to use with larger tires.

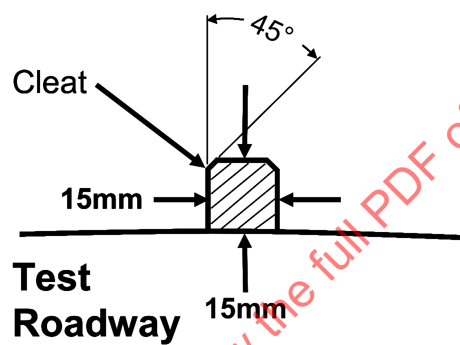

FIGURE 2 - CROSS SECTIONAL VIEW OF MOUNTED 90° CLEAT AFFIXED TO A DRUM

Test cleats must fasten to the test surface so as to prevent bending parallel to the surface of the test drum. This requires fastening the cleats to the surface not only at the edges of the surface, but also in the middle.

To prevent rocking, and to provide a firm foundation, cleats must conform to the contour of the test surface as illustrated for the 90° cleat in Figure 2. On drums this requires cleats with alternative crest angles to have double curvature to insure firm mounting. That is cleats whose crest angle is not 90° must twist around the test surface like a helical gear tooth. Obviously the situation is simpler on a flat surface, plank, where a flat mounting side is adequate for any cleat.

When testing low aspect ratio tires, a certain amount of cautious preliminary experimentation with cleat size and tire load may be required to insure that the cleats used will not lead to damage to the test wheel.

NOTE: Cleat lateral and vertical dimensions for the smaller cleat used in testing large tires should be approximately 0.04 times the tire radius at the crown. The 2 mm bevel, which is to prevent cutting and chipping, should be adequate regardless of tire size. To avoid having different cleat sizes for every tire size in a given class, for example, farm rears, base the trial cleat sizes on the tire in the class, which is of mean load carrying capacity and aspect ratio. This was done for passenger tire sizes current in 2005 to arrive at the suggested starter cross section factor based on 16, 17, and 18 inch rims and a 60 aspect ratio. It is realized that very large rim sizes and low aspect ratios now exist in the passenger car market, but it was judged that these will probably continue to be of secondary importance for the majority of customers, thus, the trial sizing factor was based on the choice noted in the last sentence.

7 This cleat duplicates the cleat size used in SAE J2730.

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6.7 Test Space

The space housing the machine shall be vibrationally characterized and monitored as specified in Section 6.1. It shall be maintained at 22 °C ± 2 °C during testing.

7. CALIBRATION

Calibrate all measuring system components in accordance with the mandates of the written plan required by the laboratory quality system referenced in Section 5. Calibration must exercise all measuring system components over substantially their full range of application and must be performed not less frequently than once each year. The reference standards and instruments used in measuring system calibration shall be traceable to the National Institute of Standards and Technology or the appropriate national standards organization for the country in which the testing is being performed. Currently valid calibration certificates for reference standards and instruments must be on file in the testing laboratory's files when the system's calibration is performed. Gains, offsets, and other pertinent performance measures and comments on system behavior during calibration shall be kept permanently on file within the testing laboratory's archives and be available to customers on request.

8. PREPARATION OF APPARATUS

Preparation of the apparatus shall ensure that the test equipment meets its calibration at the outset of each test program. The precise process control method used to verify readiness of the apparatus is likely to be unique to an individual test site, but must be specified in writing within the quality system of the laboratory. The results of process control experiments shall be available on request.

9. SELECTION AND PREPARATION OF TEST TIRES

9.1 Selection of Tires for Good Comparability

The purpose of the test must be carefully borne in mind when selecting test tires, since tire properties depend on numerous factors besides the tire design and materials. It is especially important to properly account for storage history (SAE 810066) and previous work history (SAE 770870). Due to the many complex questions that the test defined in this document may be used to address, specific tire selection recommendations can only be made for the case in which different tires are to be compared for pure design or materials effects. In that case, all test tires should be of approximately the same age, have been stored under essentially identical conditions, have experienced approximately the same exercise history, and have been sampled from production lots with similar statistical characteristics.

9.2 Inflation Pressure

The inflation pressure will significantly affect the stiffness of a tire under load and, thus, the tire's response to cleat impacts. Therefore, the appropriate test inflation pressure must be specified by the requester to allow for behavior in the environment which is being simulated. If the purpose of testing is to simulate the running state, then the inflation pressure used in the test must be equivalent to the on-road operating inflation pressure. Because tires typically operate at a temperature higher than that of the ambient air, operating inflation pressure is usually higher than cold inflation pressure. The testing laboratory shall set the test inflation pressure within ± 5 kPa of the test requester specified value.

9.3 Tire Preparation

Clean the tire surface of dirt, loose material, or other contaminants. Mount the test tire on a wheel with the tire and rim standards organization specified rim profile.[8] Mounting and demounting shall be done in accordance with the practices specified in (OSHA 1910.177). (OSHA 1910.177) does not apply to the servicing of rim wheels used on automobiles or on pickup trucks or on vans utilizing automobile tires or truck tires designated "LT".

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[8] The Tire and Rim Association, Inc. is an example of a tire and rim standards organization.

9.3.1 Inertia Data

In general inertia of the rotating parts (hub, tire, etc.) is unimportant in this low speed test.

9.4 Sample Size

Typically, a single tire selected at random from among the group of tires in each specification is an adequate sample if the goal is parametric data for producing a tire model. However, should the desire be to determine differences between tire specifications at a stated level of accuracy it will be necessary to use statistically valid sample sizes and to employ appropriate statistical analyses of the results to define the differences among specifications.

10. TEST PROCEDURE

10.1 Tire Mounting

The test tire and wheel shall be mounted to the spindle and inflated to the test requester specified test inflation using regulated inflation pressure.

10.2 Loaded Radius Determination

The test provides data at three values of fixed loaded radius, R_l[9], for each separate cleat employed. The appropriate loaded radii are determined at the zero speed. With the tire and wheel positioned such that a circumferential point one-half of the way between the largest and smallest radius of the assembly is toward the test surface, the tire shall be loaded from 0 to twice the 100% test load specified by the test requester. This shall be done in a ramp of approximately 60 sec duration with R_l vs $F_{Z"}$ data sampled at least twice per second. Based on a second order fit to the R_l vs $F_{Z"}$ data between 10% loading and 200% the R_l correspondent to 50%, 100% and 200% of the specified test load shall be determined.

10.3 Test Speeds

The test speed used will be 1 km/hr or less.[10] As noted in Section 6 the test speed does not have to be constant, however, as observed in Footnote 7 it should be as invariant as reasonably possible for anti-alising filter choice reasons.

10.4 Test (90° cleat used as an example)

The test with a cleat of any crest angle is the same except for the cleat used.

10.4.1 Mount the Cleat

10.4.2 Test at ½ the Test Requester Specified 100% Test Load

- Coincident with the surface starting position set the tire to its reference angular position, load the non-rotating tire to the R_l correspondent to the test load and lock the spindle at that radius.
- Start the test surface motion.
- Acquire data for the enveloping event.
- Stop the test surface and unload the tire.
- Return the test surface to the starting position.
- Coincident with the surface starting position set the tire to its reference angular position plus 90°, load the non-rotating tire to the l correspondent to the test load and lock the spindle at that radius.
- Start the test surface motion.
- Acquire data for the enveloping event.
- Stop the test surface and unload the tire.

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[9] Tire stiffness and, hence, loaded radius is dependent on inflation pressure, operating velocity, and tire design.

[10] These low speeds should, within the task forces' experience, prevent excitation of tire dynamics.