

# SURFACE VEHICLE RECOMMENDED PRACTICE

J2812™

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## Road Load Tire Model Validation Procedures for Dynamic Behavior

### RATIONALE

This SAE Recommended Practice was developed to provide a standard procedure to validate tire models that are used for calculating dynamic spindle loads from road surface profiles.

SAE J2812 has been reaffirmed to comply with the SAE Five-Year Review policy.

#### 1. SCOPE

This SAE Recommended Practice describes an evaluation procedure for validating tire models for use in road load simulations and assesses the relevant dynamic behavior of tires.

The laboratory test utilized is a “cleat” test, where a rolling tire on a drum encounters a cleat and the resulting dynamic forces and moments are measured. This test is described in SAE J2730, “Dynamic Cleat Test with Perpendicular and Inclined Cleats”. The test is commonly used to identify tire model parameters.

In this recommended practice, requirements for the measurement of the tire’s response are described along with data processing techniques and calculations used to quantitatively compare the tire model’s calculated response to the tire’s response measured on test. This recommended practice addresses both the tire model structure and its parameters.

**NOTE 1:** In this recommended practice, validation procedures are proposed for assessing a single cleat test response, i.e., a tire’s dynamic response for one operating condition consisting of a combination of vertical load, forward velocity, cleat size, shape, and orientation, tire pressure, etc. However, it is insufficient to validate a tire model based on a single test. In practice, this assessment should be conducted over an entire set of operating conditions which are selected in such a way as to cover the range of road load simulation applications for which the tire model will be utilized.

**NOTE 2:** The procedures defined in this recommended practice aim to assess the relevant tire dynamic behavior for road load simulations. It is recommended that the following additional tire properties be determined separately:

- Normal force and rolling radius of the steady-state rolling tire (i.e., the rolling tire in the absence of vertical excitations such as cleats) at various loaded radii and forward velocities relevant for the application.
- Static tire footprint dimensions vs. normal force. (See SAE J2704.)
- Tire quasi-static longitudinal force vs. longitudinal displacement and quasi-static lateral force vs. lateral displacement. (See SAE J2718.)
- Steady-state force and moment characteristics. (See SAE J2047.)

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## 2. REFERENCES

### 2.1 Applicable Documents

The following publications form a part of this specification to the extent specified herein. Unless otherwise indicated, the latest issue of SAE publications shall apply.

#### 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](http://www.sae.org).

SAE J670 Vehicle Dynamics Terminology

SAE J2047 Tire Performance Terminology

SAE J2704 Tire Normal Force/Deflection and Gross Footprint Dimension Test

SAE J2718 Test for Tire Quasi-Static Longitudinal Force vs. Longitudinal Displacement and Quasi-Static Lateral Force vs. Lateral Displacement

SAE J2730 Dynamic Cleat Test with Perpendicular and Inclined Cleats

## 3. DEFINITIONS

Definitions are consistent with the standards listed in 2.1.1 SAE Publications except as defined herein.

### 3.1 WHEEL-SPIN AXIS

The axis of wheel rotation. (See SAE J670.)

### 3.2 WHEEL PLANE

A plane normal to the wheel-spin axis, which is located halfway between the rim flanges. (See SAE J670.)

### 3.3 ROAD PLANE

The plane tangent to the test machine test surface (without cleat) at the shortest distance from wheel center to the test surface measured in the wheel plane. This definition is only applicable for cleat testing where the cleat width is significantly smaller than the tire contact patch.

### 3.4 AXIS SYSTEM ( $X_w$ , $Y_w$ , $Z_w$ )

The coordinate system used in this recommended practice is the SAE J670 Wheel Axis System with Z-Up orientation. The axis system is illustrated in Figure 1. Specifically:

- The origin of the coordinate system is fixed in the wheel plane at the wheel-spin axis.
- The positive  $X_w$  axis lies in the wheel plane, parallel to the road plane, in the direction of the wheel heading.
- The positive  $Z_w$  axis lies in the wheel plane, pointing away from the road plane.
- The positive  $Y_w$  axis lies in the wheel-spin axis and is chosen to make the axis system right-handed.

NOTE 3: If the origin of the coordinate system of the measured data (i.e., wheel force transducer or spindle transducer data) is not the same as the origin of the axis system defined above (origin at the wheel center), then the measured data will need to be transformed to the axis system prior to performing further analysis.

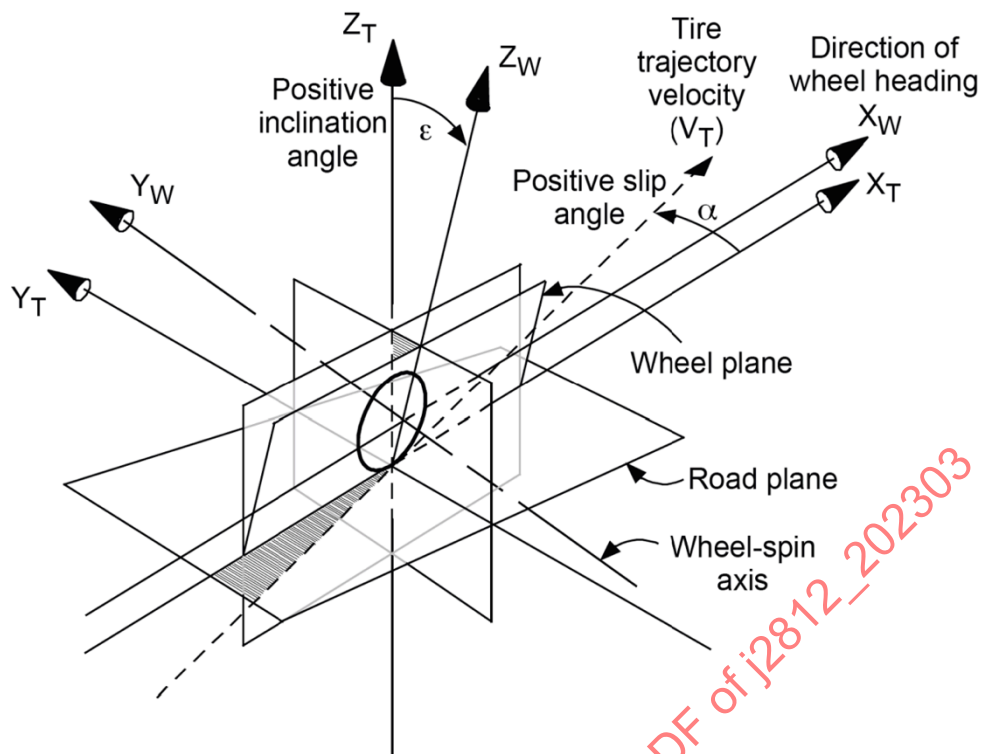


FIGURE 1 – AXIS SYSTEM (FROM SAE J670 WHEEL AXIS SYSTEM WITH Z-UP ORIENTATION)

#### 4. NOMENCLATURE

Table 1 defines symbols used in the calculations in 5.4 of this document.

TABLE 1 – SYMBOLS DEFINED

| Symbol                      | Defined Term                                                                                                  |
|-----------------------------|---------------------------------------------------------------------------------------------------------------|
| $F_{ZSS(EST)}$              | Estimated steady-state vertical force (see 5.4.1)                                                             |
| $F_{XSS}, F_{YSS}, F_{ZSS}$ | Calculated steady-state longitudinal, lateral, and vertical force <sup>1</sup>                                |
| $M_{XSS}, M_{ZSS}$          | Calculated steady-state overturning and aligning moment <sup>1</sup>                                          |
| $t$                         | Time                                                                                                          |
| $t_0, t_1, t_2, t_3$        | Specific times used to calculate steady-state vertical load                                                   |
| $t_H, t_Q, t_M$             | Specific times used to identify the time of first cleat contact                                               |
| $t_{CC}$                    | Time of first cleat contact <sup>1</sup>                                                                      |
| $\Delta t_0$                | Time interval for the on-cleat phase of a test <sup>1</sup>                                                   |
| $t_{CLEAT}$                 | Time when the tire is centered above the cleat                                                                |
| $t_{CCR}$                   | Estimated time at the end of cleat contact                                                                    |
| $Q_0$                       | Quality measure for agreement between measurement and simulation during the on-cleat interval <sup>2</sup>    |
| $W_0$                       | Weighting function for composite quality measure, on-cleat interval <sup>2</sup>                              |
| $Q_A$                       | Quality measure for agreement between measurement and simulation during the after-cleat interval <sup>2</sup> |
| $Q$                         | Composite quality measure for agreement between measurement and simulation                                    |
| $A$                         | Fitted amplitude <sup>2</sup>                                                                                 |
| $\omega$                    | Fitted frequency <sup>2</sup>                                                                                 |
| $\delta$                    | Fitted decay coefficient <sup>2</sup>                                                                         |

1. These quantities represent, or are derived from, both measured and simulated signals. As needed, M and S are appended to their subscripts to indicate measured or simulated quantities, respectively.

2. These quantities are derived from force and moment time histories. As needed, FX, FY, FZ, MX, and MZ are appended to their subscripts for elucidation.

## 5. QUANTIFICATION OF DEVIATION BETWEEN A MEASURED AND A SIMULATED CLEAT TEST

The variables defined in 5.1, 5.2, and 5.3 characterize a single cleat test. Section 5.4 describes the calculation of the deviation between measurement and simulation for a single cleat test.

### 5.1 Cleat Test Primary Influence Factors

Table 2, Figure 2, and Figure 3 define the primary factors that characterize the cleat test. Together, these values classify a given cleat test and they appear in the calculations of quality measures for agreement.

Equation 1 and 2 define measures of cleat height and width, respectively.

$$\text{Normalized Cleat Height} = \frac{\text{Cleat Height}}{\text{Tire Section Height}} \times 100 \quad (\text{Eq. 1})$$

$$\text{Normalized Cleat Width} = \frac{\text{Cleat Width}}{\text{Tire Section Height}} \times 100 \quad (\text{Eq. 2})$$

The actual cleat height and width used during the measurement may differ by up to 2.5 mm from the values indicated, if exactly the same geometry is used in the simulation. This allows the use of standard cleats with dimensions in increments of no more than 5 mm.

The figures provide an example for a cleat with a rectangular cross section. The cleat's edges may be chamfered or rounded up to 25% of its height if exactly the same cross section is used in the simulation.

TABLE 2 – CLEAT TEST CHARACTERISTICS

| Name                         | Definition                                                                                                                                                                                                                                                                                                                         | Units |
|------------------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------|
| normalized cleat height      | Maximum cleat height, relative to tire's nominal section height                                                                                                                                                                                                                                                                    | %     |
| normalized cleat width       | Maximum cleat width relative to tire's nominal section height                                                                                                                                                                                                                                                                      | %     |
| cleat orientation angle (CO) | Cleat orientation angle relative to longitudinal direction, measured counter-clockwise. CO is negative if the right cleat end reaches the tire later than the left cleat end, 90 degrees if the cleat is oriented in the transverse direction, and positive if the right cleat end reaches the tire sooner than the left cleat end | deg   |
| surface speed indicator      | Test surface speed as seen from the wheel center, relative to the tire's rated maximum speed at the tested conditions                                                                                                                                                                                                              | %     |
| wheel load indicator         | Estimated steady-state vertical spindle load relative to the tire's rated maximum load at the tested conditions                                                                                                                                                                                                                    | %     |

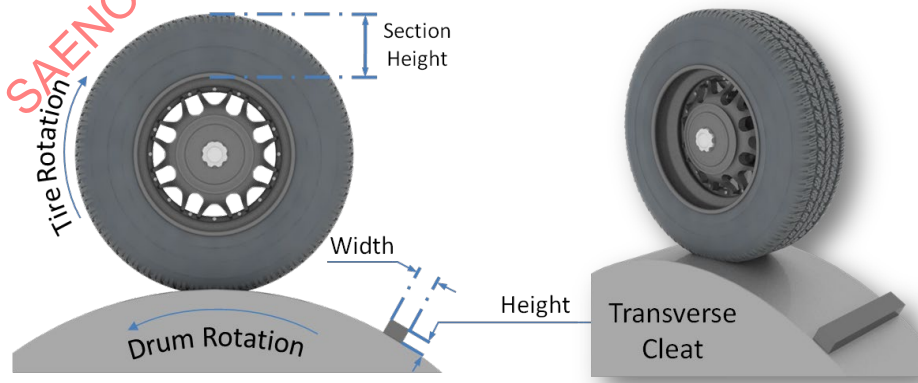


FIGURE 2 – CLEAT HEIGHT AND WIDTH, AND TIRE SECTION HEIGHT

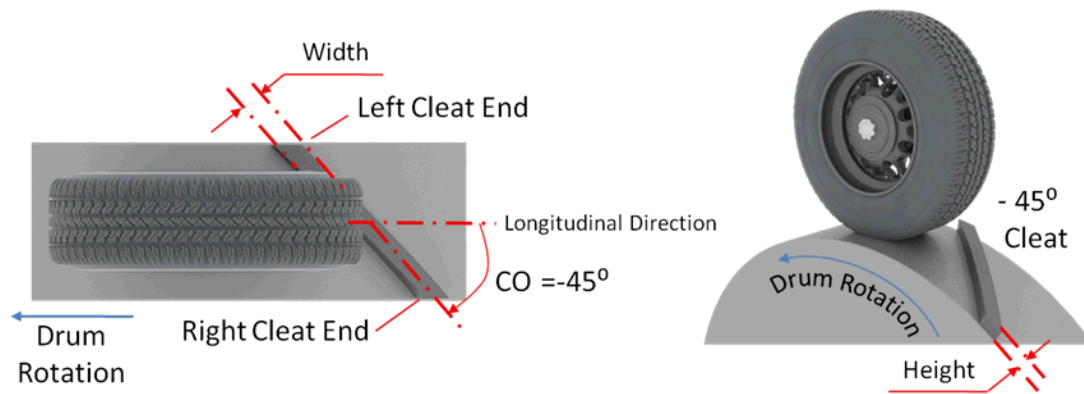


FIGURE 3 – CLEAT ORIENTATION ANGLE (CO), SHOWN IMMEDIATELY BEFORE IMPACT

## 5.2 Cleat Test Secondary Influence Factors

Tables 3 and 4 define secondary factors that influence the cleat test. These quantities do not appear in subsequent calculations, but they must be reported with the results of each comparison.

### 5.2.1 Test Rig Characterization

TABLE 3 – TEST RIG PROPERTIES

| Name                                                       | Definition/notes                                                                                                                                                                                 | Units             |
|------------------------------------------------------------|--------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|-------------------|
| test rig type                                              | 0: flat surface, 1: outer drum, 2: inner drum                                                                                                                                                    | -                 |
| drum diameter                                              | Only required for drum-type rigs                                                                                                                                                                 | m                 |
| wheel moment of inertia                                    | Moment of inertia of the wheel used for testing (not including the tire), about the wheel spin axis                                                                                              | kg-m <sup>2</sup> |
| hub moment of inertia                                      | Moment of inertia of all parts rotating about the wheel spin axis excluding the inertia of the test tire and wheel about the spin axis                                                           | kg-m <sup>2</sup> |
| rotating drum moment of inertia (optional)                 | Rotating drum moment of inertia about the drum spin axis                                                                                                                                         | kg-m <sup>2</sup> |
| longitudinal compliance (optional)                         | Longitudinal displacement of the wheel center per longitudinal force applied to the wheel center under non-rolling (static) conditions                                                           | m/N               |
| lateral compliance (optional)                              | Lateral displacement of the wheel center per lateral force applied to the wheel center under non-rolling (static) conditions                                                                     | m/N               |
| vertical compliance                                        | Vertical displacement of the wheel center per vertical force applied to the wheel center under non-rolling (static) conditions                                                                   | m/N               |
| inclination compliance (optional)                          | Rotation of the rim about the longitudinal axis per moment about the longitudinal axis under non-rolling (static) conditions                                                                     | deg/N-m           |
| drum (rig) surface type                                    | Type of surface on the drum (rig) that makes contact with the tire, i.e. polished steel, 80 or 120 grit safety tread, etc.                                                                       | -                 |
| drum (rig) surface sliding friction coefficient (optional) | Friction coefficient for the tire sliding on the drum (rig) surface; at 0.1 m/s at 50% rated load when the wheel is locked. Handbook or estimated values may be used and shall be noted as such. | -                 |
| cleat surface sliding friction coefficient (optional)      | Friction coefficient for the tire sliding on a flat surface made of the same material as the cleat surface; at 0.1 m/s at 50% rated load when the wheel is locked.                               | -                 |

## 5.2.2 Nominal Tire Operating Conditions

TABLE 4 – TIRE OPERATING CONDITIONS

| Name               | Definition/notes                                                                     | Units |
|--------------------|--------------------------------------------------------------------------------------|-------|
| inflation pressure | Tire inflation pressure, unloaded at 20°C ambient temp.                              | kPa   |
| inclination angle  | Nominal tire inclination angle relative to the rig surface as specified in SAE J2047 | deg   |
| slip angle         | Nominal tire slip angle as specified in SAE J2047                                    | deg   |

## 5.3 Required Measurements

Report pre-test tire inflation pressure and post-test inflation pressure for each testing session, or every four hours, whichever is shorter. For this purpose, measure the inflation pressure of the unloaded tire immediately before and immediately after running a series of tests (a test session).

Table 5 lists the time-domain signals that must be recorded during the test according to SAE J2730. The validation report shall contain graphs of these signals versus time.

TABLE 5 – REPORTED TIME-DOMAIN SIGNALS

| Symbol   | Name                                   | Definition/notes                                                                         | Units   |
|----------|----------------------------------------|------------------------------------------------------------------------------------------|---------|
| $V_s$    | test surface speed                     | Drum surface velocity – drum angular velocity multiplied by the mean drum surface radius | m/s     |
| $\omega$ | wheel spin velocity                    | Angular velocity of wheel derived from RPM or angular position measurement               | rad/s   |
| $a_x$    | wheel center longitudinal acceleration | Translational acceleration of the wheel center in the $X_w$ direction                    | $m/s^2$ |
| $a_y$    | wheel center lateral acceleration      | Translational acceleration of the wheel center in the $Y_w$ direction                    | $m/s^2$ |
| $a_z$    | wheel center vertical acceleration     | Translational acceleration of the wheel center in the $Z_w$ direction                    | $m/s^2$ |
| $F_x$    | longitudinal force                     | Longitudinal spindle force at the wheel center                                           | N       |
| $F_y$    | lateral force                          | Lateral spindle force at the wheel center                                                | N       |
| $F_z$    | vertical force                         | Vertical spindle force at the wheel center                                               | N       |
| $M_x$    | overturning moment                     | Moment about the longitudinal axis at the wheel center                                   | N-m     |
| $M_y$    | rolling moment (optional)              | Moment about the wheel spin axis                                                         | N-m     |
| $M_z$    | aligning moment                        | Moment about the vertical axis at the wheel center                                       | N-m     |

NOTE 4: Although it is desired to measure the accelerations at the wheel center, in practice, this is generally not possible. Accelerometers are usually placed on the spindle housing of the test machine, as close to the wheel center as possible. In such a case, the distances of the accelerometer to the wheel center should be measured and reported with respect to the wheel coordinate system. These measurements are required to gage the stiffness of the test machine as described in SAE J2730 section 6. The first natural frequency of the test machine spindle should ideally be at least three times the first natural frequency of the tire being tested.

## 5.4 Computation of Single Cleat Test Simulation Accuracy

### 5.4.1 Steady-State Offset Elimination

The force and moment signals may include all, only part, or none of the total steady-state load component, depending on measurement equipment and procedures. In order to focus on the dynamic properties of the time signals, any steady-state load component is identified and eliminated by the procedure defined in this section. Perform this procedure for both the simulated and measured signals individually.

The calculations require an estimate of steady-state vertical force ( $F_{ZSS(EST)}$ ) for the measured and simulated case. This will typically be the product of the rated maximum load and the wheel load indicator. (See Table 2.)

Search the global vertical force trace for the maximum value. Designate the corresponding time as  $t_3$  and the force value as  $F_Z(t_3)$ .

Seek the instant when the vertical force first surpasses a quarter of its rise above the estimated steady state value:

$$t_1 = \min\{t; F_Z(t) \geq F_{ZSS(EST)} + (F_Z(t_3) - F_{ZSS(EST)})/4\} \quad (\text{Eq. 3})$$

and half of the its rise above the estimated steady state value:

$$t_2 = \min\{t; F_Z(t) \geq F_{ZSS(EST)} + (F_Z(t_3) - F_{ZSS(EST)})/2\} \quad (\text{Eq. 4})$$

Estimate the start of the dynamic response:

$$t_0 = t_2 - 2(t_2 - t_1) \quad (\text{Eq. 5})$$

Figure 4 illustrates the process. Calculate the steady-state value of vertical force by averaging over a 0.1-s interval, ending 0.01 s in advance of  $t_0$ . For example:

$$F_{ZSS} = \frac{1}{0.1 \text{ sec}} \int_{t_0-0.11}^{t_0-0.01} F_Z(t) dt \quad (\text{Eq. 6})$$

Figure 5 provides an example of this process. Calculate  $F_{XSS}$ ,  $F_{YSS}$ ,  $M_{XSS}$ , and  $M_{ZSS}$  by averaging over the same time interval.

Repeat this calculation for both the measured and simulated signals, store the 10 calculated steady-state values, and remove the steady-state component from each time-domain signal. The steady-state values for the measured signals appear in 5.4.7 with “M” appended to the subscript.

All subsequent calculations in this section assume that the steady-state component has been removed.

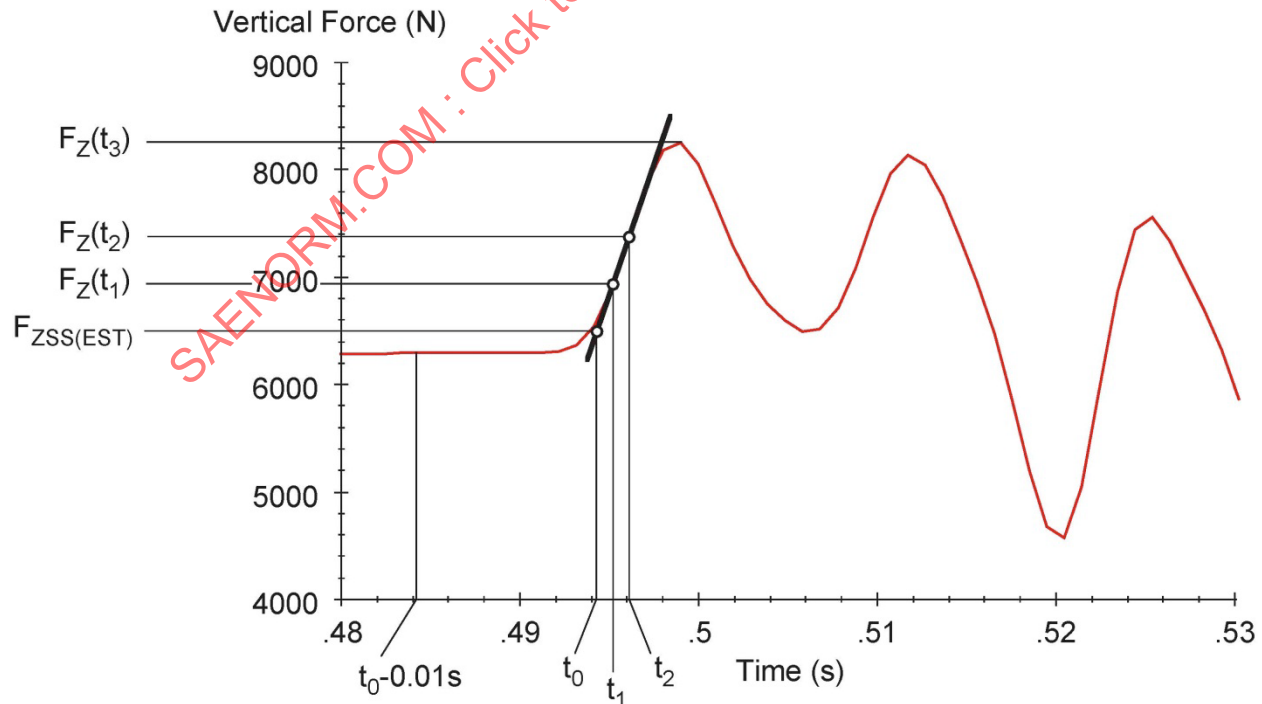


FIGURE 4 – STEADY-STATE OFFSET ELIMINATION – START OF DYNAMIC RESPONSE

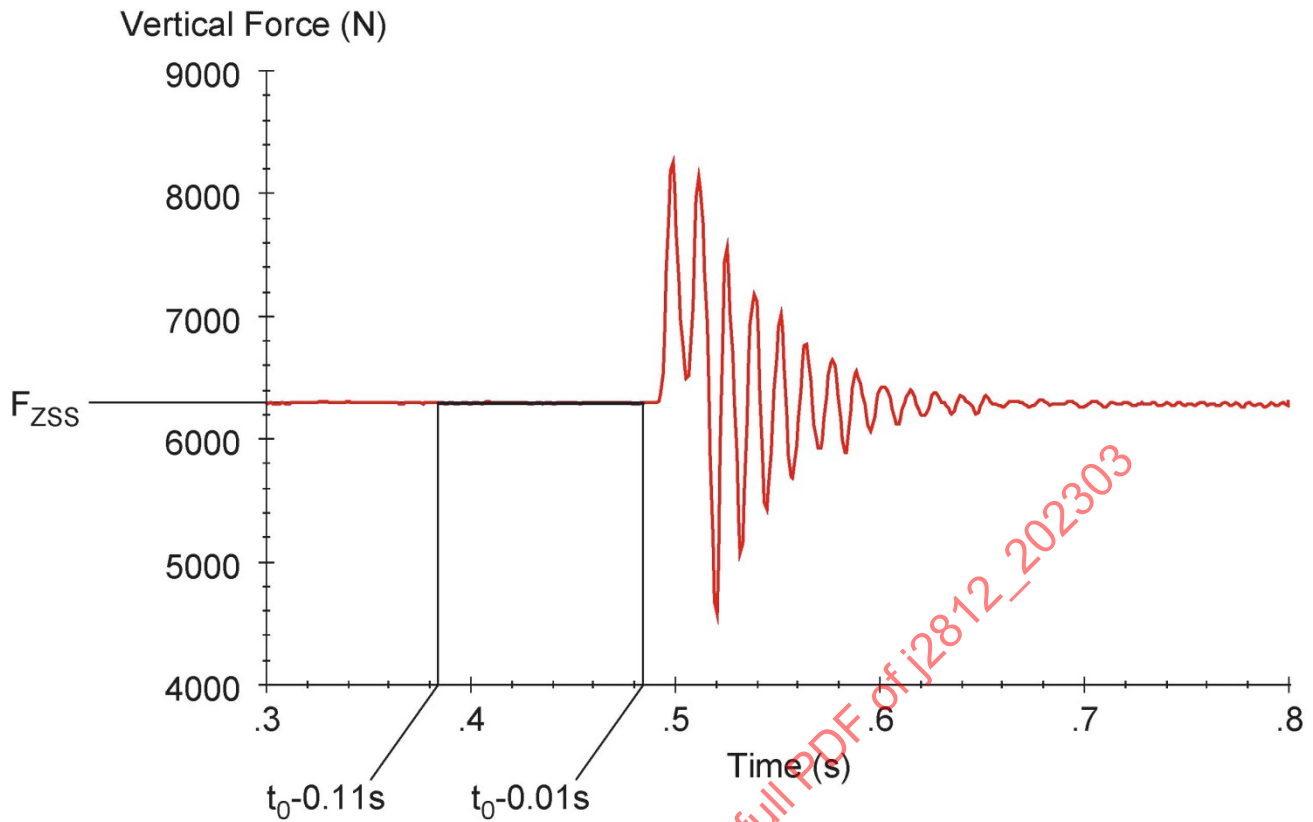


FIGURE 5 – STEADY-STATE OFFSET ELIMINATION - AVERAGING

#### 5.4.2 Time of First Cleat Contact

After elimination of the steady-state offset in the time domain signals (5.4.1), the time of first cleat contact ( $t_{cc}$ ) for measurement and simulation is defined by re-evaluating the vertical force signals.

Search the global vertical force trace for the maximum value. Designate the corresponding time as  $t_m$  and the force value as  $F_z(t_m)$ .

Seek the instant when the vertical force first surpasses a quarter of its rise:

$$t_Q = \min\{t; F_z(t) \geq F_z(t_m)/4\} \quad (\text{Eq. 7})$$

and half of its rise:

$$t_H = \min\{t; F_z(t) \geq F_z(t_m)/2\} \quad (\text{Eq. 8})$$

As shown in Figure 6, this procedure is very similar to the procedure in 5.4.1, with the exception that the steady-state value has been calculated and eliminated, rather than estimated.

Time of first cleat contact is calculated by extrapolating backward in time from  $t_Q$ , and assuming a rise to  $F_z(t_Q)$  with the same slope leading to  $t_Q$  as occurred between  $t_Q$  and  $t_H$ :

$$t_{cc} = t_H - \frac{t_H - t_Q}{F_z(t_H) - F_z(t_Q)} F_z(t_H) \quad (\text{Eq. 9})$$

If any of the above values cannot be determined uniquely, the cleat test is not to be used for validation.

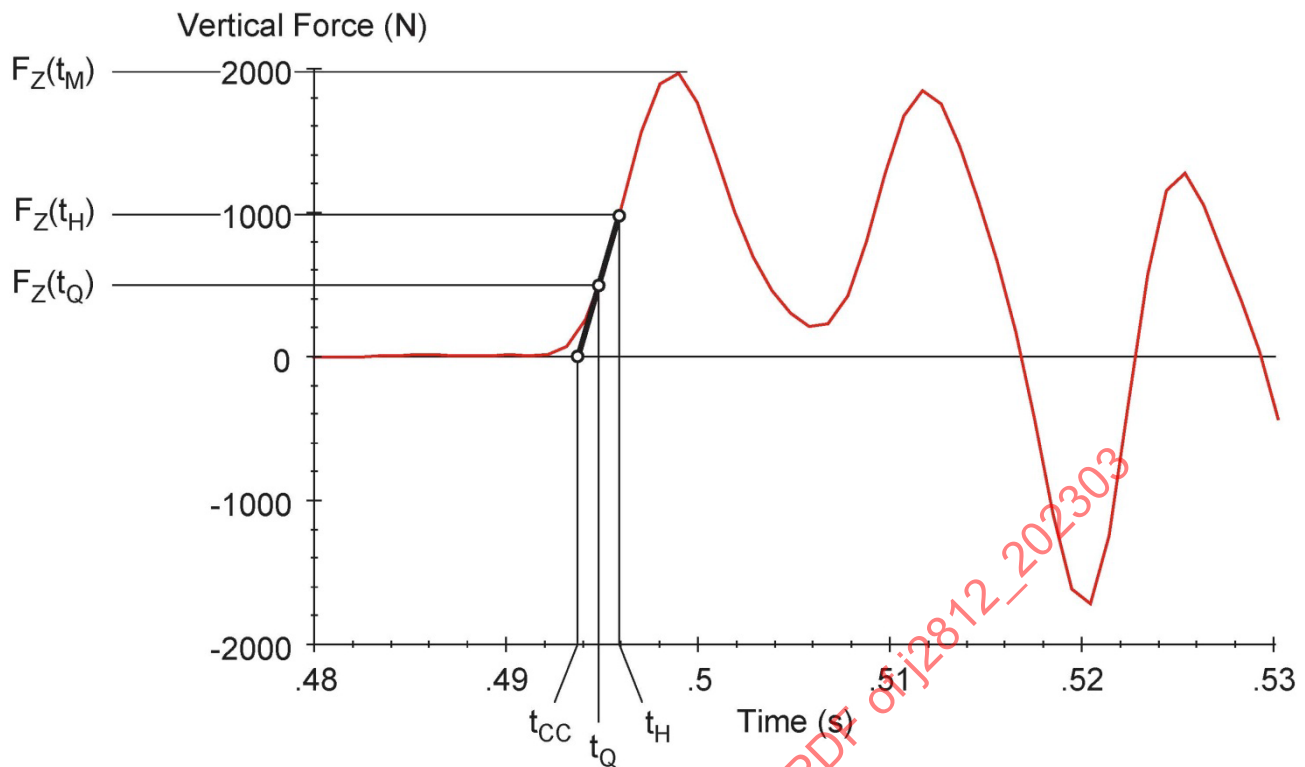


FIGURE 6 – TIME OF FIRST CLEAT CONTACT

#### 5.4.3 Cleat Test Phases

A single cleat test is divided into three phases. Simulation and measurement are compared separately in the on-cleat phase and after-cleat phase.

##### 5.4.3.1 Before-Cleat Phase

The before-cleat phase begins 0.1 s before first cleat contact and ends at the instant immediately before first cleat contact.

##### 5.4.3.2 On-Cleat Phase (O)

The on-cleat phase (O) includes contact between the tire and the cleat and the short time interval immediately following contact defined as follows. This is the time interval,  $\Delta t_O$  between  $t_{CC}$  and the first time  $F_x(t)$  crosses zero after it has reached its maximum value. (See Figure 7.) Derive the value of this interval for the measured signal ( $\Delta t_{OM}$ ) and the simulated signal ( $\Delta t_{OS}$ ).

##### 5.4.3.3 After-Cleat Phase (A)

During the after-cleat, or post-pulse oscillation phase, cleat-induced vibrations die out. The after-cleat phase is defined as the 0.2-s interval immediately after the on-cleat phase. (See Figure 7.)

#### 5.4.4 Cleat Contact Synchronization

Prior to comparing measured and simulated tire forces, the signals have to be synchronized.

#### 5.4.4.1 Synchronization Using Measured Cleat Position

The preferred method for performing synchronization is by using the measured cleat position. The cleat position is defined by the drum position at which the center of the cleat passes directly below the wheel center. If cleat position is to be used for synchronization, it is necessary to determine the location of the cleat within  $\pm 1$  mm.

In the measured signals, the cleat position is determined by using the time " $t_{\text{CLEAT}}$ ", which corresponds to the moment at which the cleat passes the wheel center. Since the method to perform the cleat position measurement is not defined in SAE J2730, a recommended practice is proposed in section 6 of this document. Simulation results must also include a time indication of cleat position so that measurement and simulation results can be aligned in time.

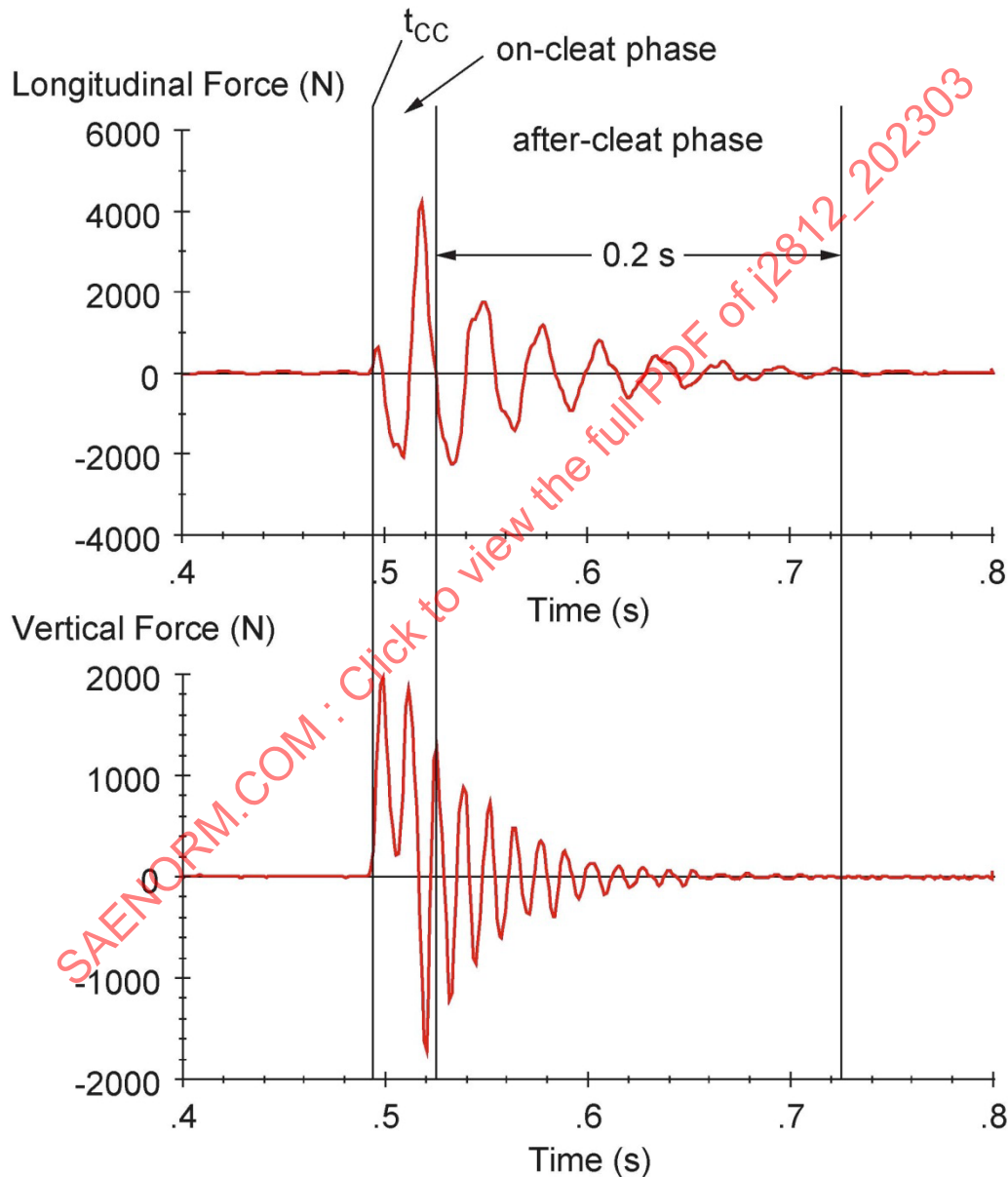


FIGURE 7 – CLEAT TEST PHASES

#### 5.4.4.2 Synchronization Using Alternative Method

When no cleat position measurement is available, an alternative method may be used in which the simulation results are shifted along the time axis for consistency with the measured signal. This shift is performed by aligning the point in time of first cleat contact of the simulation ( $t_{CCS}$ ) with the respective point in time of the measurement ( $t_{CCM}$ ). Without further refinement, both times coincide after the shift, this common point in time is called  $t_{CC}$ , and  $\Delta t_o$  is the larger of  $\Delta t_{OM}$  and  $\Delta t_{OS}$ .

As a refinement of this alignment, a second alignment can be performed by maximizing the cross correlation of the vertical force between  $t_{CC}$  and  $t_{CCR}$ , where  $t_{CCR}$  is calculated by:

$$t_{CCR} = t_{CC} + \frac{W + 2\sqrt{2R(H + D) - (H + D)^2} + B / |\tan(CO)|}{V} \quad (\text{Eq. 10})$$

Where the following definitions apply:

- V: Surface speed
- W: Maximum cleat width
- H: Maximum cleat height
- R: Nominal tire radius
- B: Nominal tire width
- D: Tire deflection
- CO: Cleat orientation angle (see Table 2)

After this refinement of the alignment the points in time of first cleat contact of measurement and of simulation, as well as the estimated points in time of end of cleat contact, will not coincide anymore. The common points in time of first cleat contact ( $t_{CC}$ ) and the interval of cleat contact ( $\Delta t_o$ ) are thus defined as:

$$t_{CC} = \min\{t_{CCS}, t_{CCM}\} \quad (\text{Eq. 11})$$

$$\Delta t_o = \max\{t_{CCS} + \Delta t_{OS}, t_{CCM} + \Delta t_{OM}\} - t_{CC} \quad (\text{Eq. 12})$$

#### 5.4.5 Assessment of Variability of Measured Data

The run to run variations of the 16 impact events that are recorded for each test condition per SAE J2730 are evaluated for both the before-cleat phase and for the total event (all phases). The before-cleat phase is analyzed separately to focus on tire non-uniformities.

##### 5.4.5.1 Force and Moment Variation During the Before-Cleat Phase

For each of the 16 impacts, calculate the RMS difference between the measured longitudinal force and the steady state longitudinal force, which was determined using Equation 6. Use the same before-cleat time interval as was used in Equation 6. Repeat the calculations for the vertical force, lateral force, overturning moment, and steer moment. Report the  $F_x$ ,  $F_y$ ,  $F_z$ ,  $M_x$  and  $M_z$  RMS variations for each of the 16 impacts during the before-cleat phase.

##### 5.4.5.2 Force Variation During All Phases

As described in SAE J2730, calculate a sample by sample average time trace of longitudinal force for the 16 cleat impacts. Calculate the RMS difference between each the 16 measured longitudinal force traces and the average of the 16 impacts. Repeat the calculations for the vertical force, lateral force, overturning moment, and steer moment. Report the  $F_x$ ,  $F_y$ ,  $F_z$ ,  $M_x$  and  $M_z$  RMS variations for each of the 16 impacts for the complete event (all phases).