



SURFACE VEHICLE RECOMMENDED PRACTICE

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Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks

RATIONALE

The path curvature of an automobile in steady turning is determined by speed, steering-wheel angle, wheelbase, and the elastic and kinematic characteristics of the front and rear steering systems, suspensions, and tires.

When turning at very low lateral acceleration levels, tire slip angles are negligible and the vehicle follows the *Ackermann turn radius*, which is defined geometrically by wheelbase and by front and rear steer angles. When turning at appreciable speed, tire slip angles are no longer negligible and produce cornering forces that cause kinematic and elastic deflections in the steering, suspension, and tire systems that modify the front and rear steer angles. The difference between the total front and rear effects determine what is often referred to as the *understeer/oversteer* characteristic of the vehicle. The test procedures described herein are designed to measure objective responses of the vehicle that quantify this *understeer/oversteer* characteristic.

SAE J266 has been reaffirmed to comply with the SAE Five-Year Review policy.

1. SCOPE

This SAE Recommended Practice establishes consistent test procedures for determination of steady-state directional control properties for passenger cars and light trucks with two axles. These properties include the steering-wheel angle gradient, reference steer angle gradient, sideslip angle gradient, vehicle roll angle gradient, and steering-wheel torque gradient with respect to lateral acceleration. They also include the yaw velocity gain, lateral acceleration gain, and sideslip angle gain with respect to steering-wheel angle. Additionally, the characteristic or critical speed and the front and rear wheel steer compliances may be determined.

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 International

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J670

Vehicle Dynamics Terminology

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2.2 Related Publications

The following publications are provided for information purposes only and are not a required part of this SAE Technical Report.

2.2.1 SAE Publications

Available from SAE International, 400 Commonwealth Drive, Warrendale, PA 15096-0001, Tel: 877-606-7323 (inside USA and Canada) or +1 724-776-4970 (outside USA), www.sae.org.

SAE J2181	Steady-State Circular Test Procedure for Trucks and Buses
SAE Paper 670078	The Influence of Vehicle Design Parameters on Characteristic Speed and Understeer, R. T. Bundorf
SAE Paper 760713	The Cornering Compliance Concept for Description of Vehicle Directional Control Properties, R. T. Bundorf and R. L. Leffert
SAE Paper 741096	A Primer on Nonlinear, Steady-State Vehicle Turning Behavior, R. W. Topping
SAE Paper 720473	A New Laboratory Facility for Measuring Vehicle Parameters Affecting Understeer and Brake Steer, A. L. Nedley and W. J. Wilson
SAE Paper 741104	Understanding Tire Intermix Through the Cornering Compliance Concept, R. L. Leffert, P. M. Riede, and R. E. Rasmussen

2.2.2 ISO Publications

Copies of these documents are available online at <http://webstore.ansi.org/>.

ISO 4138:2012	Passenger Cars - Steady-State Circular Driving Behaviour - Open-Loop Test Methods
ISO 7401:2011	Road Vehicles - Lateral Transient Response Test Methods - Open-Loop Test Methods
ISO 8855:2011	Road Vehicles - Vehicle Dynamics and Road-Holding Ability - Vocabulary
ISO 14792:2011	Road Vehicles - Heavy Commercial Vehicles and Buses - Steady-State Circular Tests
ISO 15037-1:2006	Road Vehicles - Vehicle Dynamics Test Methods - Part 1: General Conditions for Passenger Cars

3. DEFINITIONS

The terminology used herein follows the standard definitions as found in SAE J670, with the following addition:

3.1 ACKERMANN TURN RADIUS (R_A)

The path radius at a given steering-wheel angle, when operating at negligible speed.

4. GENERAL

4.1 Test Methods

Five test methods are described:

- Method 1 - Constant Radius Test
- Method 2 - Constant Steering-Wheel Angle Test
- Method 3 - Constant Speed, Variable Radius Test
- Method 4 - Constant Speed, Variable Steering-Wheel Angle Test
- Method 5 - Yaw Velocity Gain/Speed Test

The first four methods yield substantially similar data, but they differ in requirements for testing space, driver skill, and instrumentation. Methods 1 and 3 depend upon the path-keeping ability of the driver to minimize instrumentation requirements. Methods 2 and 4 use fixed steering-wheel angle and measure path radius with inertial instruments. Method 5 utilizes the ratios of the various responses to steering-wheel angle. Method 4 is generally run at 80 to 100 km/h. Method 5 is limited to the 0 to 0.4 g “linear range” of vehicle operation, but can be run at considerably higher speeds than the other methods. The data plot of Method 5 (see Figure D5) also demonstrates most clearly the concepts of *characteristic speed* and *critical speed*, as defined in SAE J670.

4.2 Relationship to Other Standards

This document is a superset of International Standard ISO 4138:2012 and a complement to International Standard ISO 7401:2011. Methods 1 through 4 are similar to the procedures described in ISO 4138. Method 4 is conducted in a manner similar to the step input test protocol described in ISO 7401, but the procedure described herein is used to extract only steady-state vehicle characteristics, whereas ISO 7401 extracts only transient response characteristics. SAE J2181:1998 describes the procedures of Methods 1 and 2 adapted for buses and heavy trucks, including articulated vehicles. ISO 14792:2011 describes versions of Methods 1, 2, 3, and 4 adapted for heavy commercial vehicles and buses. This ISO document incorporates the concept of equivalent wheelbase, which was just emerging in the literature at the time of the development of SAE J2181:1998.

4.3 Theoretical Basis for the Test Procedures

The path curvature of an automobile in steady turning (that is, in a given state of equilibrium, or *steady state*) is determined by speed, steering-wheel angle, wheelbase, and the elastic and kinematic characteristics of the front and rear steering systems, suspensions, and tires.

In the absence of elastic and kinematic steer effects - for example, at very low lateral accelerations - the *Ackermann turn radius* (R_A in Figure A1) is defined geometrically by wheelbase and by front and rear steer angles. With increasing speed, steady turning requires the generation of centripetal force, which produces deflections in the steering, suspension, and tire systems. As described in SAE Paper 670078, these include lateral force compliance steer, aligning torque compliance steer, suspension roll steer, tire slip angles from lateral force and camber force, etc. When expressed in deg/g of lateral acceleration and lumped together, these “cornering compliances” produce front and rear steer angles and tire slip angles. Cornering compliances subtract from the front and rear *Ackermann wheel steer angles* as shown in Figure A1. Greater cornering compliance in the front than in the rear increases path radius from the Ackermann condition, and produces *understeer*, while greater cornering compliance in the rear than in the front reduces path radius, causing *oversteer*. The difference between the total front and total rear cornering compliance is called the *understeer/oversteer gradient*, expressed in deg/g. Likewise, the change in steering-wheel angle required to maintain a given radius with increasing lateral acceleration is called the *steering-wheel angle gradient*, the change in vehicle roll angle with lateral acceleration is called the *roll angle gradient*, etc.

The test procedures described herein are designed to measure these various vehicle response gradients.

The sensitivities of the vehicle's responses to steering inputs are called *yaw velocity gain* (deg/s per degree of steering-wheel angle), *lateral acceleration gain* (gs per degree of steering-wheel angle), *sideslip angle gain*, etc. These can be calculated from the vehicle speed, steering-wheel angle, steering ratio, wheelbase, and understeer/oversteer gradient, or they can be obtained directly from measured data.

4.4 Equivalence of Test Procedures

In theory, the nature of any stable steady state is independent of the method by which it is achieved. Therefore, to obtain a desired set of steady-state conditions of speed, steering-wheel angle, and path radius, it is possible to hold any one of them constant, vary a second, and measure the third. Thus one may use a *constant radius test*, in which speed is varied and steering-wheel angle is measured; a *constant steering-wheel angle test* in which speed is varied and path radius is measured; a *constant speed, variable radius test* in which path radius is varied and steering-wheel angle is measured; or a *constant speed, variable steering-wheel angle test* in which steering-wheel angle is varied and path radius is measured. All of these test methods will produce equivalent results, provided they span the same range of steady-state conditions as defined by speed, steering-wheel angle, and path radius. In fact, one may, in principle, obtain an equivalent to any of the tests by cross-plotting a series of one of the other tests: for example, one could take points at constant speed from a series of constant radius tests run on different turn radii.

In practice, results obtained from significantly different combinations of speed, steering-wheel angle, and path radius may differ somewhat due to differences in road-load throttle, aerodynamics, tire slip, and steer and inclination angles at different steering-wheel angles, etc. Gradients obtained for a given steady-state condition, but by different methods, may differ because, in some methods, lateral acceleration is controlled by changing speed and in other methods, by changing steering-wheel angle. Practical considerations such as tire heating during long test runs and failure to maintain true steady state also may affect test results.

4.5 Steering Systems

Understeer/oversteer gradients may be stated in terms of the difference in cornering compliances between the front and rear axles. However, cornering compliances include deflections of the steering system under lateral forces and aligning torques. In order to include steering system compliances, understeer/oversteer gradients are determined from measurements at the steering wheel. Steering-wheel angles are related to the road wheel steer angles by the *overall steering ratio*.

Overall steering ratio is a variable which describes the geometric relationship between steering-wheel angle and average road wheel steer angle, measured under conditions of zero aligning torque and lateral force at a given steering-wheel angle. Overall steering ratio varies continuously over the range of steering wheel angles, and shall be determined for the range of steering-wheel angles used during the test. It does not imply a steering system with a fixed ratio: in many vehicles the steering system is significantly nonlinear, due to steering arm geometry, universal joint relationships, or a variable ratio steering gear. If the steering system is significantly nonlinear, each measured steering-wheel angle must be used together with a plot of average road wheel steer angle versus steering-wheel angle to obtain the corresponding road wheel steer angle. Appendix E discusses the topics of steering system kinematics, their measurement, and associated terminology.

4.6 Vehicles with Four-Wheel Steering

Current four-wheel steering systems can be divided into three general types: rear steer having a programmed relationship to steering-wheel angle; rear steer programmed according to lateral acceleration; and rear/front steer ratio programmed according to speed or other, more complex, relationships. The first type creates a combined net-effect front-rear steering ratio (Figures A1 and A2) which is in general nonlinear, and which may be treated as discussed in 4.5. The second type can be treated as only an additional source of rear wheel compliance steer. However, the third type must be considered as a separate control input. For steady-state testing of this third type of vehicle, it may be necessary to disable the rear steering to measure "basic" response parameters, then by additional testing with rear steer enabled, determine the rear-steer control algorithm and measure its effect on steady-state response parameters. Alternatively, tests of vehicles with systems of the third type may be conducted by holding the state that affects the rear steer ratio constant during the test. For example, vehicles with a speed-varying rear steer ratio may be tested using a constant-speed test method. Repeat tests at several different speeds would define the vehicle characteristics at different operating conditions. Depending on the complexity of the system being evaluated, some of the above methods may be impractical.

4.7 Vehicle Reference System

The variables of motion used to describe vehicle steady-state behavior in these test methods relate to the intermediate axis system (X, Y, Z) (refer to SAE J670).

For these test methods, the vehicle reference point is defined as the location of the static vehicle center of gravity at the test load condition.

5. INSTRUMENTATION

5.1 Description

The variables selected for test purposes shall be monitored using appropriate transducers, and the data shall be recorded on a multi-channel recorder having a time base. The frequency response of the entire measurement system, including transducers, data filters, and recorder, shall have amplitude errors (combined attenuation and ripple) less than $\pm 0.5\%$ in the relevant frequency range of 0 to 5 Hz. If the recording system involves sampling rather than continuous recording of all data channels, pre-sampling, anti-aliasing filters are required. For 0.5% data accuracy, the anti-aliasing filters must ensure that any noise components at frequencies greater than 1/2 the sampling frequency have amplitudes less than 0.5% of the signal amplitude. The order and passband of the filters, and the sampling rate, shall be selected together to provide the required performance.

All pre-recording analog filters shall have sufficiently similar phase characteristics to ensure that time delay differences lie within the required accuracy for time measurements. Additional filtering for data evaluation and analysis shall utilize phaseless (zero phase shift) methodologies.

Corresponding samples of all data channels which are to be compared in analysis shall be taken simultaneously, or separated in time by a delay sufficiently short to maintain the required data accuracy. (Note that the maximum rate of amplitude change of a 5 Hz signal is 3% per millisecond.)

The typical operating ranges and recommended maximum errors of the transducer/recording system are shown in Table 1.

Table 1 - Variables

Variable	Typical Operating Range	Recommended Maximum Error of the Combined Transducer/recorder System
Steering-wheel angle	± 180 deg	± 1.0 deg
Lateral acceleration	± 10 m/s ²	± 0.10 m/s ²
	± 1.0 g	± 0.01 g
Yaw velocity	± 50 deg/s	± 0.5 deg/s
Forward velocity	0 to 50 m/s	± 0.5 m/s
Lateral velocity	± 10 m/s	± 0.1 m/s
Sideslip angle	± 15 deg	± 0.5 deg
Vehicle roll angle	± 15 deg	± 0.15 deg
Front wheel steer angle	± 10 deg	± 0.2 deg
Rear wheel steer angle	± 10 deg	± 0.2 deg
Steering-wheel torque	± 30 Nm	± 0.3 Nm

5.2 Transducers and Their Installation

Transducers of various types, some commercially available and some specially fabricated, are used in measuring the required variables. If a transducer does not directly measure the required variable, appropriate corrections and/or transformations shall be made to its signal to obtain the required variable with a sufficient level of accuracy.

Because of the variety of instrumentation possibilities, the type of each instrument used shall be recorded; and where applicable, its location on the vehicle shall be entered on the test data sheets.

Typical errors for various direct measurement transducers are given in the following paragraphs. Net percentage error for a variable computed from the output signals of transducers is found by taking the differential of the computed variable and dividing it by the computed variable.

5.2.1 Steering-Wheel Angle

Steering-wheel angle is measured relative to the sprung mass. Typical transducers are multi-turn potentiometers or digital shaft encoders, geared to the back of the steering wheel or attached to a “second steering wheel.”

5.2.2 Forward Velocity and Path Velocity

A forward-velocity transducer should be installed as close as possible to the mid-track position on the vehicle. If not located at mid-track, its location must be recorded and its signal corrected as necessary in data processing. Typical transducers are fifth wheels with accuracies to 0.05 m/s, “contactless” velocity transducers based upon optical principles with accuracy of 0.025 to 0.15 m/s, and systems based on the Global Positioning System (GPS) with accuracies of 0.01 to 0.1 m/s. The steady-state fifth wheel signal is very close to the horizontal velocity along the curved-path vehicle trajectory, while optical transducers measure the component of this “path velocity” in the X_v direction (horizontal velocity multiplied by the cosine of the vehicle sideslip angle).

5.2.3 Sideslip

Sideslip angle at a given point can be measured directly by means of a bipolar velocity transducer based upon optical principles, installed according to the manufacturer's specifications. The transducer location must be recorded. Sideslip velocity at any other point can be obtained by interpolation between two velocity transducers; or by extrapolation from the sideslip velocity at the point of measurement by adding the product of yaw velocity times the distance to the desired point. Sideslip angle is computed as the angle whose tangent is lateral velocity divided by forward velocity. Commercially available bipolar velocity transducers have a range of ± 250 km/h and $\pm 2.5\%$ full-scale steady-state accuracy.

Sideslip angle can also be measured directly by a castered trolley, attached to the vehicle through gimbals and loading springs to keep the caster axis vertical. The sideslip angle measured is that which exists at the caster axis. The sideslip angle at any other point on the longitudinal axis of the vehicle can be computed by interpolation between two trolleys, or from the sideslip angle at the point of measurement and the yaw velocity as in the preceding paragraph. The vehicle sideslip angle is defined as that obtained for the vehicle reference point. Steady state sideslip trolley accuracies of 0.25 degree are possible.

Vehicle sideslip velocity can also be computed by integration of a lateral acceleration signal (corrected for position, vehicle roll angle, and surface inclination errors) minus the product of speed and yaw velocity. Vehicle sideslip angle is then computed as above. This method is suitable only for short-term tests, because the net acceleration error including zero offsets is integrated.

5.2.4 Yaw Velocity

Yaw velocity is measured by an angular rate transducer, installed as specified by the manufacturer. Traditional angular rate sensors are rate gyroscopes: typical good performance has linearity of 0.2 to 0.5% full-scale to 1/2 full scale and 1 to 2% to full scale; cross-axis sensitivity of 0.04%; thresholds of 0.05% full scale; and hysteresis 0.15% full scale. Solid-state sensors based on beam deflections, tuning fork-Coriolis effect, or other principles are also commercially available, with linearity of $\pm 0.05\%$ to $\pm 0.1\%$ full scale, threshold 0.01 deg/s, and no hysteresis. Angular rate transducers fixed in the vehicle measure yaw velocity in the vehicle axis system: therefore in steady-state turning they measure yaw velocity multiplied by the cosine of the vehicle roll angle. The signal must be corrected for vehicle roll and pitch angles in order to obtain yaw velocity in the ground plane.

When sideslip transducers are installed at both front and rear, yaw velocity may be computed from the difference in front and rear sideslip velocity, divided by the longitudinal distance between the transducers.

5.2.5 Lateral Acceleration

Lateral acceleration can be measured by an accelerometer having sufficient accuracy over a sufficient bandwidth which includes steady state, and installed in one of the following ways.

- a. Mounted on the sprung mass with its sensitive axis aligned with the vehicle Y_V -axis. If it is not located at the vehicle center of gravity, its output will have an error due to yaw acceleration, and if it is not on the roll axis, an error will be caused by roll acceleration. Even though these errors should not exist under steady-state conditions, the accelerometer location should be recorded. The position-corrected signal must be corrected for the component of gravity due both to the sine of the vehicle roll angle plus that of track surface inclination.
- b. Mounted on a platform stabilized by a gyroscope system. Position correction considerations are as in (a). Consideration must be given to gyroscope erection and drift errors, as described in 5.2.6.

High-quality “servo” accelerometers have linearities of ± 0.05 to $\pm 0.1\%$ full scale, with 0.02% hysteresis and 0.01% resolution. Solid-state (MEMS) accelerometers typically have linearities of $\pm 1\%$ of full scale. Measurement errors can be dominated by installation conditions: for example, a 0.6 degree error in roll angle compensation will cause a 0.01 g acceleration measurement error.

Steady-state centripetal acceleration may be obtained as the product of horizontal velocity and yaw velocity. Steady-state centripetal acceleration differs from lateral acceleration by the cosine of the vehicle sideslip angle. This correction factor may be applied in data processing, or for sufficiently small sideslip angles (e.g., cosine 5 degrees is 0.996) the difference may be ignored.

When traveling at steady state on a known constant radius, centripetal acceleration may be obtained from horizontal velocity squared divided by the path radius, or from yaw velocity squared multiplied by the path radius.

5.2.6 Roll Angle

Roll angle with respect to the gravity vertical can be measured by a two-axis gyroscope, either a case-referenced free gyroscope or gravity-referenced vertical gyroscope. The free gyroscope element is caged, or locked to its case when not measuring. When uncaged, it remains fixed in inertial space, enabling measurement of angular vehicle motion. A free gyroscope may be used to measure roll and yaw, or roll and pitch motion. A vertical gyroscope is “erected” to a gravity vertical by pendulous switches which when activated control slow-acting torque motors. Neither type can maintain the required measurement accuracy for long periods of steady turning. Free gyroscopes and vertical gyroscopes with deactivated erection systems tend to “drift” at a rate usually specified by the manufacturer at 0.5 to 1 deg/min maximum; and vertical gyroscopes with activated erection systems seek an “apparent vertical” which is the sum of the gravity and lateral acceleration vectors, at a rate of 2 to 5 deg/min. In the absence of lateral acceleration, vertical gyroscope erection accuracy is typically specified at ± 0.15 to ± 1 deg.

The roll angle with respect to the road surface can be measured by:

- a. An angular measurement transducer installed in the roll gimbal of a sideslip trolley.
- b. Measurement of changes in the vertical distance to the ground from reference points on either side of the vehicle, using ultrasonic or optical transducers.
- c. Measurement of suspension ride motion with respect to the sprung mass, taking into account suspension linkage factors. (This method does not account for tire deflections, and is a measurement of suspension roll angle.)

In each of these methods it is practical to attain the specified accuracy, with no restriction on test run duration.

Change in roll angle from a test initial condition can be measured by integration of the signal from a roll rate gyroscope. This method is suitable only for short-term tests, since the entire signal including any zero offsets will be integrated.

5.2.7 Steering-Wheel Torque

Steering-wheel torque is measured by a torque load cell, installed as specified by the manufacturer to measure the torque applied to the steering wheel about its axis of rotation.

5.2.8 Road Wheel Steer Angles

Road wheel steer angles with respect to the sprung mass can be obtained by angle measurement transducers, attached between the sprung mass and spindle assemblies or mounted in bearings to the wheel hubs and attached to the sprung mass through restraints which permit unrestricted fore/aft, vertical, and camber motions; or by linear or angular displacement transducers mounted in the steering linkage.

The resultant front steer angle due to force and moment compliance and suspension kinematics is computed by subtracting steering-wheel angle divided by front axle steering ratio from total front road wheel steer angle. For vehicles having variable ratio steering, see 4.5.

The resultant rear steer angle due to force and moment compliance and suspension kinematics is the same as rear road wheel steer angle, except for vehicles having four-wheel steering (see 4.6).

5.2.9 Tire Slip Angles

Tire slip angles can be measured directly by available optical transducers. Alternatively, they can be computed as the difference between the sideslip angle referred to the front and rear wheel locations and the respective total road wheel steer angles (see 5.2.3).

5.2.10 Inertial Plus GPS Measurement Systems

The combination of GPS with accelerometer/angular rate triads yields a number of accurate measurements. A typical system has high-quality servo accelerometers and MEMS angular rate sensors, with integration to obtain velocities and position, and pitch, roll and heading angles. Sampled GPS data are used with Kalman filters to correct integration drift. Achievable direct measurement accuracies are those of the basic inertial transducers. Computed data can have estimated one-sigma RMS accuracies of 0.05 to 0.2 km/h in forward velocity, 0.2% in lateral velocity, ± 0.03 degree in roll and pitch angles, ± 0.1 degree in heading angle, and ± 0.2 degree in slip angle.

6. TEST CONDITIONS

6.1 Test Vehicle Documentation

The as-manufactured description of the vehicle under test shall be entered on the Test Vehicle Specification Sheet (see Figure B1).

The overall steering ratio shall be measured according to Appendix E and recorded on the Test Vehicle Specification Sheet (see Figure B1). For vehicles having rear steer with fixed relationship to front steer, both front and rear steer angles shall be measured and recorded (see 4.6 and Figure A1).

The as-tested condition: the tire size, type, brand information, inflation pressure, and tread depth; any special equipment; any deviation in type or operating condition of components from manufacturer's specification; the vehicle wheel loads; the odometer reading at the beginning and end of the test; the speed and direction of the ambient wind; and any other condition that may affect test results, shall be recorded on the Test Conditions Sheet (see Figure C1).

The instrumentation transducers used, their locations in the vehicle, and any other significant instrumentation information shall be entered on the Instrumentation Information Sheet (see Figure C2).

6.2 Test Track

All tests shall be carried out on a uniform hard surface that is free of contaminants and that has a gradient, in any direction, of not more than 2%. For a standard test condition, a smooth, dry pavement of asphalt or cement concrete or a high-friction test surface is recommended. The effect of ambient wind must be considered at all test speeds: ambient wind speed at vehicle height should normally not exceed 7 m/s, and for high-speed testing a lower maximum wind speed is desirable. Surface and wind data should be noted on the Test Conditions Sheet (see Figure C1).

6.3 Tires

The test may be performed with tires in any state of wear so long as, at the end of the test, a minimum of 1.5 mm of tread depth remains over the entire tread surface, excluding wear bars.

However, for a standard tire condition, since tire force and moment properties can vary significantly during the early use of a tire, new tires shall be used after being conditioned by means of the tire warm up procedure (see 7.2.1). The conditioning and warm up shall be performed with each tire mounted in the appropriate position on the test vehicle, or an equivalent vehicle, and without excessive harsh use which might affect test results.

For a standard vehicle condition, tires shall be inflated to have the cold pressure specified by the vehicle manufacturer for the test vehicle configuration at the ambient temperature of the testing area. The tolerance for setting the cold pressure is ± 5 kPa for pressures up to 250 kPa, and $\pm 2\%$ for pressures above 250 kPa.

Tire wear state and inflation pressure significantly influence the test results. Therefore tire wear state, break-in procedure, testing sequence, and inflation pressure shall be recorded on the Test Conditions Sheet (see Figure C1), and any non-standard conditions shall be specifically noted therein.

6.4 Operating Components

All operating components and adjustments likely to influence the test results (for example: wheel rims, springs, suspension parts, wheel alignment) shall be inspected to ensure that they meet the manufacturer's specifications. All components shall be properly adjusted and secure. All instrumentation and ballast must be secured, for safety and to prevent shifts in the vehicle center of gravity.

6.5 Vehicle Loading Condition

6.5.1 Minimum Loading Condition

The total vehicle mass for the minimum loading condition shall consist of the complete vehicle curb mass plus the masses of the driver and instrumentation. Instrumentation shall be located to produce a loading distribution approximately equivalent to 2 passengers in the front seats.

6.5.2 Maximum Loading Condition

For the maximum loading condition of passenger cars, the total vehicle operating mass of the fully laden vehicle shall consist of the vehicle curb mass, plus 68 kg for each seat in the passenger compartment, plus the maximum luggage mass specified by the manufacturer equally distributed over the luggage compartment. Loading of the passenger compartment should be such that the actual wheel loads are equal to those obtained by loading each seat with 68 kg. The mass of the driver and instrumentation shall be included in the vehicle operating mass.

Light trucks shall be loaded to the Gross Vehicle Mass Rating. The distribution of load shall not cause the Gross Axle Mass Rating to be exceeded at either the front or the rear axle.

Care shall be taken to give minimum error in the location of the center of gravity and in the values of the moments of inertia as compared to the loading conditions of the vehicle in normal use. The location and center of gravity height of the equivalent passenger loads and cargo load should be noted in the Test Conditions Sheet (see Figure C1).

6.5.3 Fifth Wheel

If a fifth wheel is used as a velocity transducer, the vehicle should be weighed with the fifth wheel down.

7. TEST PROCEDURES

7.1 General Testing Procedures

All necessary variables shall be recorded throughout the maneuver. Data shall be taken for both left and right turns.

For test methods utilizing discrete increments of speed, radius, or steering-wheel angle, all the test data may be taken in one turn direction followed by all the data in the other direction. Experience has shown that this procedure minimizes data scatter. However, to obtain more even tire wear and reduce tire heating, data may be taken in alternate turn directions at each test speed/radius/steering-wheel angle. The method chosen shall be noted on the Test Conditions Sheet (see Figure C1).

At a minimum, data shall be taken at increments of lateral acceleration no larger than 0.05 g. Where the data change very rapidly with changes in lateral acceleration, it may be useful to decrease the speed/radius/steering-wheel angle increments.

It is recommended that the test be repeated several times so that the results can be examined for repeatability and averaged.

Caution should be exercised during testing to minimize tire heating as much as possible. Tire heating is a particular concern for test methods using continuous speed increase with attendant long periods of data acquisition, and for all test methods at high levels of lateral acceleration. The tires should be allowed to cool to normal operating temperature between test runs.

7.2 Preliminary Test Procedures

7.2.1 Tire Conditioning and Warm Up

The tires shall be conditioned prior to the test by a procedure equivalent to driving a minimum of 15 minutes at a speed of 100 km/h, followed by 500 m in each direction at an average lateral acceleration of 0.3 g. Caution should be exercised during the warm up procedure to minimize exposure of the tires to lateral accelerations exceeding 0.4 g to avoid abnormal tire wear. For light trucks ballasted to GVWR, lower average and maximum lateral accelerations may be considered for conditioning. The resulting initial hot inflation pressure shall be recorded and entered on the Test Conditions Sheet (see Figure C1). It is recommended that hot inflation pressure be rechecked at intervals during the test program and final cold inflation pressure be checked at the end of the test program. Any significant changes should be noted on the Test Conditions Sheet (see Figure C1).

7.2.2 Instrument Zeroes

Instrument zeroes should be recorded after driving the vehicle at a slow speed in a straight line and bringing it gently to a stop. To eliminate any surface inclination effects, the procedure must be performed in opposite directions at the same location, and the results averaged.

Instrument zeroes must be recorded before the test, after allowing sufficient time for transducer and signal conditioner warm-up, gyroscope spin-up, etc., and also at the end of the test. It is recommended that they be recorded during the test program, at intervals appropriate to the quality of the instrumentation used. For maximum accuracy, zeroes should be taken immediately before and after each test run, so that any drift can be compensated by straight-line approximation.

7.3 Constant Radius Test

7.3.1 Test Description

This procedure requires the test vehicle to be driven at several speeds over a circular path of known radius. The directional control response characteristics are determined from data measured at successively higher speeds on a constant-radius path. The Constant Radius Test exists in two variations. In the first, the vehicle is driven onto the circular path at each constant speed, data are taken when steady state is attained and the vehicle is driven off. This procedure minimizes tire heating, permits vehicle roll angle measurement by free gyroscope or vertical gyroscope, and it can be run on any level constant-radius path of sufficient length to attain and hold on-radius steady state for at least a 3 s measurement period, but the procedure is time-consuming. In the second variation, the vehicle remains on the circle, attaining a series of discrete steady-state speeds, or a continuous, slow speed increase, during which data are taken.

The Constant Radius Test requires minimal instrumentation, since yaw velocity and lateral acceleration can be computed from speed and path radius. The associated disadvantage is the human element - path radius errors are difficult to monitor. The success of the method depends on the driver's ability to maintain the specified constant radius within the required percentage error, and at lateral acceleration levels near the vehicle limit of control this task may be difficult. GPS or other direct position measurements can be used to quantify the actual path radius and thereby reduce the errors associated with this task. Use of a radius that is too small involves unrealistically low speeds, causes larger percentage errors in radius, and increases difficulty in course-keeping, especially at high lateral accelerations. The minimum recommended radius is 30 m.

7.3.2 Test Procedure

The vehicle shall first be driven on the desired circular path at the lowest possible speed. Data shall be recorded with the steering-wheel position and throttle position fixed to record the approximate included Ackermann steer angle at the steering wheel. The overall steering ratio, derived from front and rear steering kinematic functions, can be used to determine the included Ackermann steer angle.

The vehicle shall then be driven at the next speed at which data are to be taken. The level of the lateral acceleration shall be increased and data shall be taken until it is no longer possible to maintain steady-state conditions.

7.3.2.1 Discrete Test Procedure. After determining the approximate included Ackermann steer angle, the vehicle shall be driven onto the circle at each test speed from an initially straight path, and recorded data shall include the initial, straight-line readings. At each test speed, after attaining steady state in which the desired path radius is held within ± 0.5 m, the steering-wheel and throttle positions shall be held constant for at least 3 seconds. All necessary variables shall be recorded throughout the maneuver.

7.3.2.2 Continuous Test Procedure. After establishing the approximate included Ackermann steer angle, the vehicle shall be accelerated to the next test speed, while remaining on the circle. At each test speed, after regaining the steady-state path radius within ± 0.5 m, the steering wheel and throttle positions shall be held as constant as possible while data are taken. Data shall be taken for at least 3 seconds at each steady-state lateral acceleration level. If speed is steadily increased, the rate of increase shall not exceed 1.5 km/h per second, and data shall be recorded continuously, so long as the vehicle remains "on radius." Vehicle roll angle, if recorded, shall be measured by a drift-free method.

7.4 Constant Steering-Wheel Angle Test

7.4.1 Test Description

This procedure requires that the test vehicle be driven at several speeds with a single, fixed steering-wheel angle. The path radius is determined by computation from horizontal velocity (see 5.2.2) and yaw velocity (see 5.2.4) or by direct measurement, such as with GPS-based instrumentation. The Constant Steering-Wheel Angle Test exists in two variations: a series of discrete runs or a single continuous test run. In the first, the steering-wheel angle is applied with the vehicle traveling in an initial, straight line and is maintained until steady-state conditions are reached. Then the steer is removed (or reversed) and the procedure is repeated. In the second, the steering-wheel angle is held fixed while speed is increased continuously at a slow rate, or at a series of steady-state levels, up to the limit of control. The first procedure minimizes tire heating, permits roll-angle measurement by free gyroscope or vertical gyroscope, and requires less test area, but it requires a mechanical steering stop for precise repetition of steering-wheel angle. The second procedure is simpler to run.

The Constant Steering-Wheel Angle Test requires little driver skill, and lateral acceleration can be taken up to the vehicle's limit of control if sufficient space is available. For vehicles having high levels of understeer, or understeer which increases markedly at high lateral acceleration, large increases in path radius occur with increasing speed. In the continuous test method, the recommended initial path radius is 30 minutes. Other radii may be used, with 20 minutes as a minimum. The path radius required for testing to the limit of control can be 100 minutes or more.