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SURFACE VEHICLE RECOMMENDED PRACTICE

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Submitted for recognition as an American National Standard

Steady-State Circular Test Procedure for Trucks and Buses

1. *Scope*—This test procedure is used to determine the steady-state directional control response of vehicles by measuring steady-state cornering behavior. Due to the wide range of operational conditions to which a vehicle can be subjected, the results of this testing do not provide a complete description of a vehicle's total dynamic behavior; in particular, the procedure does not test the vehicle's response during transient maneuvers. To fully assess a vehicle's total dynamic behavior, it would be necessary to conduct other test procedures in order to evaluate the vehicle's performance as a whole.

The extent of instrumentation and the required accuracy of the measurement will be dependent on the goals of the personnel conducting the test. If it is desired simply to determine the general performance characteristics of a vehicle, then this test can be conducted with minimal instrumentation and test item preparation.

1.1 Purpose—This SAE Recommended Practice establishes a uniform procedure for determining the steady-state directional control response of trucks, buses, and combination vehicles.

2. References

2.1 Applicable Publications—The following publications form a part of the specification to the extent specified herein. Unless otherwise indicated, the latest revision of SAE publications shall apply.

2.1.1 SAE PUBLICATION—Available from SAE, 400 Commonwealth Drive, Warrendale, PA 15096-0001.

SAE J266—Steady-State Directional Control Test Procedures for Passenger Cars and Light Trucks

2.1.2 ANSI PUBLICATION—Available from ANSI, 11 West 42nd Street, New York, NY 10036.

ISO 4138—Road vehicles—Steady-state circular test procedure

3. *Instrumentation*

3.1 General—The variables to be measured during testing shall be monitored using the appropriate transducers, and the data shall be recorded on a multi-channel recorder incorporating a time base.

The primary goal of this test procedure is to determine the relationship between steering wheel angle and lateral acceleration. Measurement of the absolute value of the steering wheel angle relative to the zero-steer position does not require a particularly high degree of accuracy; indeed, finding a true zero-steer angle to be used as an exact point of reference can be difficult due to the considerable steering system compliance typically present on heavy vehicles. What is of importance is to measure the change in steering wheel angle that occurs as lateral acceleration increases; alternatively, if the steering angle is held constant during testing, the change in turn radius that occurs as lateral acceleration increases. Given these requirements, the instrumentation should be selected so that it is highly accurate in measuring changes in the steering wheel angle or turn radius.

Typical operating ranges and recommended maximum errors of the transducer/recording system are listed in Table 1.

TABLE 1—INSTRUMENTATION RANGE AND ACCURACY[1]

Variable	Range	Recommended maximum error of the combined transducer and recorder system
Steering wheel angle	test item dependent	±0.5 degree
Lateral acceleration	±1.0 g	±0.02 g
Yaw velocity	±20 degrees/s	±0.1 degree/s
Forward road speed	0 to 110 km/h (0 to 68 mph)	±1.8 km/h (±1.1 mph)
Sideslip angle	±15 degrees	±0.5 degree
Articulation angle	±30 degrees	±0.5 degree
Steering wheel torque	±30 N.m (±22 ft-lb)	±0.3 N.m (±0.22 ft-lb)
Roll angle	±20 degrees	±0.15 degree
Turn radius	30 to 300 m (98 to 984 ft)	±1% of value

1. The level of accuracy required will be dependent on the goals of the test personnel. Values listed in Table 1 are intended to be used as a general reference for testing

The minimum overall bandwidth of the complete measurement system shall be 3 Hz. If a digital data acquisition system is used, it is recommended that the data be filtered at approximately 5 Hz, and sampled at a minimum of four times the filter frequency to avoid aliasing. Alternatively, if broad-band data are captured, the data should be filtered before processing. It is recommended that a cutoff frequency of approximately 2 Hz be used during this filtering to attenuate the effects of sprung mass bounce and pitch.

3.2 Installation—Transducer installation and orientation will vary according to the type of instrumentation in use and the manner in which the test is conducted. However, if a transducer does not directly measure the required variable, appropriate corrections for linear and angular displacement shall be applied to its signals so that the required level of accuracy is obtained.

"Offtracking" occurs when the trailing units of an articulated vehicle do not follow the exact path of the prime mover. Offtracking will cause the lateral accelerations present in the trailing units to differ from that of the prime mover. If it is desired to measure these parameters, it will be necessary to install the appropriate instrumentation on each unit of the vehicle combination.

3.2.1 STEERING WHEEL ANGLE—A transducer shall be installed to obtain steering wheel angle relative to the sprung mass of the vehicle. Depending on the steering ratio of the test item, the transducer may be required to record deflections greater than 360 degrees from the centered steering position.

3.2.2 LATERAL ACCELERATION—An accelerometer capable of measuring constant levels of acceleration may be installed on the vehicle or on each unit of an articulated vehicle. The transducer may be installed:

a. On the sprung mass at the center of gravity of the vehicle (unit) and aligned with the y-axis of the vehicle (unit), as defined by the SAE reference axis system. In this case, it will measure "side acceleration" and its output shall be corrected for the component of gravity on the accelerometer axis due both to vehicle roll angle and any track surface inclination.
b. On the sprung mass of the vehicle (unit) at any position and aligned parallel to the vehicle (unit) y-axis. In this case, its output shall be corrected for its position relative to the center of gravity, which will give "side acceleration," which in turn shall be corrected for the component of gravity on the accelerometer axis due both to vehicle roll angle and any track surface inclination.
c. On a reference trolley such as may be used to measure vehicle roll angle and sideslip angle. In this case, corrections shall be made both for its position relative to the vehicle (unit) center of gravity and for any track surface inclination.

Imperfections in the road surface of test tracks will often cause oscillatory rolling of the test vehicle's sprung mass. These oscillations will cause accelerations to be superimposed on the lateral acceleration data. To minimize the effect that these roll motions have on test data, the accelerometer may be placed coincident with the roll axis of the vehicle. Data shall then be corrected for accelerometer position relative to the center of gravity.

3.2.3 YAW VELOCITY—A yaw velocity transducer may be installed on the vehicle, or on each unit of an articulated vehicle, with its axis aligned with or parallel to the vehicle (unit) z-axis.

3.2.4 FORWARD SPEED—A road speed transducer may be installed on the vehicle or on the front unit of an articulated vehicle. If the transducer is not aligned so as to operate in the x-z plane and parallel to the test track surface, its output shall be corrected for any linear or angular displacement therefrom.

3.2.5 SIDESLIP ANGLE—A transducer may be installed so as to measure the sideslip angle (β-angle) of the vehicle. When testing an articulated vehicle, it is recommended that the sideslip transducer be mounted to the front unit. If the transducer does not measure the angle in the plane of the road surface, an appropriate correction shall be made. Sideslip angle can be calculated from coincident measurements of other variables; for example, lateral and forward velocity at any point on the vehicle. The point of the vehicle to which the output of the transducer is referred shall be indicated in the test results.

3.2.6 ARTICULATION ANGLE—If testing an articulated vehicle, a transducer may be installed so as to measure the angle between the x-axes of each unit of the vehicle combination.

3.2.7 STEERING WHEEL TORQUE—A transducer may be installed so as to measure the torque applied to the steering wheel about its axis of rotation.

3.2.8 ROLL ANGLE—A transducer may be installed so as to measure the angle between the y-axis of each unit's sprung mass and the track surface. This transducer may be required if the output of other transducers require correction for roll angle.

When installing transducers, the output of which are affected by vehicle roll or track surface inclination, it may be useful to mount the transducers on a gyroscopically stabilized platform. Such a platform would reduce the extent to which test data would require correction during processing.

4. ***Facilities*—**All tests shall be conducted on a uniform hard surface which is free of contaminants and which has a gradient of not more than 1% in any direction. Ideally, the test course should be planar and have no undulations. For a standard test condition, a smooth, dry asphalt or concrete paved surface is recommended. Depending on the goals of the personnel conducting the test, it may be useful to measure the Skid Number of the test surface.

5. Vehicle Preparation

5.1 Tires—The test may be performed with the tires in any state of wear; however, it is recommended that a minimum of one-half of the original tread depth remains over the circumference of the tire at the completion of testing. Since the state of wear of the tires can have a strong influence on test results, their condition at the beginning and end of testing should be recorded.

If it is desired to test with the tires in a standard condition, new tires that have been run-in for 150 to 200 km (90 to 120 miles) in the appropriate position on the test vehicle shall be used. During this run-in period, the tires shall not be subjected to excessive loading or abuse.

Tires shall be inflated to the settings specified by the vehicle or tire manufacturer for the test vehicle configuration. The tolerance for setting the cold pressure is ±0.05 bar (0.73 psi) for pressures up to 2.5 bar (36.3 psi) and ±2% for pressures above 2.5 bar (36.3 psi).

5.2 Operating Components—All operating components likely to influence the results of this test (for example, the steering system, shock absorbers, springs, and suspension parts) shall be inspected to ensure that they meet the manufacturer's specifications and are properly adjusted and secured.

5.3 Vehicle Loading Conditions—The load configuration used during testing will be determined by the needs of the test program. Since the test results are highly dependent on load configuration, it is essential to record the characteristics of the payload. It is suggested that at a minimum the wheel load distribution, overall center of mass location, and type of payload (i.e., rigid cargo, liquid, loose gravel, etc.) be recorded. It is recommended that the condition of loose cargo be monitored throughout testing to note any shifting or settling. In particular, gravel payloads often pack down as the vehicle is operated, which in turn affects the overall center of mass and the rigidity of the payload.

5.4 Roll-Over Prevention—Since heavily laden trucks and trailers often roll over at their limits of cornering, it is recommended that a safety-outrigger system be installed to prevent a catastrophic roll-over of the test vehicle. The outrigger system should not restrict vehicle roll until the vehicle has reached roll instability. The extent to which the outriggers affect the location of the center of mass must also be considered. A reduction or redistribution of the payload may be required to achieve the desired overall vehicle weight and center of mass.

6. ***Test Procedure*—**Determine steering ratio (see Appendix A).

Tire operating temperatures can have a significant effect on test results. As a starting point, it is suggested that the tires be warmed up prior to testing by driving the vehicle in a manner consistent with its normal operation, with lateral accelerations being limited to approximately 0.25 g. Since tire temperatures will be affected by many factors during the test (including ambient conditions, the time elapsed between successive data points, and the length of each test run), they should be monitored and recorded throughout testing. The sensitivity of the test results to tire temperature may be determined by repeating test runs at a variety of tire operating temperatures; however, the effect of tire wear accumulated during these additional test runs should be considered in these comparisons.

It is not required for the vehicle to complete a circle once a steady-state condition has been achieved; however, data shall be obtained with the vehicle in a steady-state cornering condition for no less than 3 s. The ambient wind speed shall not exceed 25 km/h (15.5 mph); for larger radii where vehicle speeds are higher, a lower maximum wind speed is desirable.

6.1 Two-Axle Vehicles—The vehicle shall be driven on the desired radius (30 m [98 ft] recommended minimum) at the lowest speed that provides smooth operation. Data shall be recorded with the steering wheel position and road speed held as constant as possible.

Following completion of the initial test speed, the vehicle shall be driven at the next higher test speed. The increments between test speeds shall result in increments of lateral acceleration of no greater than 0.05 g. Equation 1 may be used to compute subsequent test speeds.

$$U_{i+1} \leq [U_i^2 + 0.05gR]^{1/2} \quad \text{(Eq. 1)}$$

where:

U_i = speed corresponding to test "i," m/s
U_{i+1} = speed for subsequent test "i+1," m/s
g = acceleration of gravity (9.81 m/s^2)
R = turn radius, m

The level of lateral acceleration shall be increased incrementally until it is no longer possible to maintain steady-state conditions. Where the data vary rapidly with increases of the lateral acceleration, it may be useful to take data in smaller increments.

This test may be conducted by either maintaining a constant steering angle for all test speeds and recording the radius of the resulting path, or by using steering corrections to hold the vehicle to a specific turn radius for all test speeds. Regardless of the method selected, the steering wheel position and road speed should be maintained as constant as possible while data are recorded, and the steered axle should follow the intended path within 0.3 m (1.0 ft) of either side. It is recommended that the highest gear compatible with the conditions of the test be used.

Testing shall be conducted for both left and right turns. To avoid abnormal tire wear patterns, data should be taken in each turn direction for each acceleration level, with successive test runs progressing from the lowest to the highest levels of lateral acceleration.

If an accelerometer is not used during testing, the side acceleration may be determined by calculating the "centrifugal" acceleration generated during operation on the skidpad, and correcting for vehicle sideslip if necessary. Centrifugal acceleration may be calculated by measuring the time required for the vehicle to complete one lap of the circular test course, and applying Equation 2.

$$a = (2\pi/t)^2(R/g) \quad \text{(Eq. 2)}$$

where:

a = acceleration, g
t = lap time, s
R = radius of test course, m
g = acceleration of gravity (9.81 m/s^2)

Side acceleration may then be calculated by multiplying the value obtained for the "centrifugal" acceleration by the cosine of the sideslip angle. If the test instrumentation lacks a sideslip measurement capability, separate measurements may be performed to obtain the sideslip angle. In general, this measurement technique involves comparing the trajectory of two points on the vehicle, with one point located towards the front of the vehicle and the other point located a distance (L) towards the rear of the vehicle. These points should be selected so that they are located on or parallel to the x-axis of the vehicle. With the vehicle operating at the appropriate road speed on the test course, the two points will describe circular paths, which must be recorded. The difference (d) in the radii of these circular paths is then determined. The sideslip angle (β) can then be calculated by using Equation 3.

$$\beta = \sin^{-1}(d/L) \qquad \text{(Eq. 3)}$$

A suggested technique for marking the trajectory of these points is to use a water dispensing system at each of the points to be tracked. The dispensing system may consist of a water reservoir gravity-feeding a small diameter hose, with the hose end rigidly located a few centimeters above the road surface. When activated, the water dispensing system deposits a thin trail of water on the road surface as the vehicle operates on the test course. Using this technique, the value for "d" can be measured directly from the two water trails on the road surface.

6.2 **Multi-Axle Vehicles—**Due to interactions between axles, the steering characteristics of vehicles having more than two axles cannot be adequately characterized by testing on a single turn radius. Rather, it is necessary to acquire data at a specific road speed on turns of various radii; therefore, the test procedure is modified accordingly.

The vehicle shall be driven at a constant road speed with the steering deflected slightly from the centered position; data shall be recorded once the vehicle has achieved steady-state cornering. While maintaining the same road speed, the steering shall then be deflected to a slightly greater angle, and data shall again be recorded. Additional test runs shall be performed at the same road speed but with greater angles of steer, up to the angle which results in either vehicle instability or a turn radius of 30 m (98 ft). It is suggested that steering angles resulting in turn radii of 300, 240, 180, 120, 60, and 30 m (984, 787, 591, 394, 197, and 98 ft) be used.

Upon completion of testing at the first speed, testing shall be repeated at a higher speed; it is recommended that the test speeds be increased in increments of 10 km/h (6.2 mph) up to and including the maximum speed of the vehicle (note that due to the power consumed by cornering, some vehicles may be unable to maintain a desired test speed through turns of tighter radii).

Testing shall be conducted for both left and right turns. To avoid abnormal tire wear patterns, data should be taken in each turn direction for each acceleration level, with successive test runs progressing from the lowest to the highest levels of lateral acceleration.

Since it is necessary to conduct testing for a large number of turn radii, several test courses must be marked on the test area. Alternatively, turn radii may be calculated from vehicle data, using parameters such as forward speed (corrected for sideslip angle) and yaw velocity or lateral acceleration (corrected for roll angle). Turn radii may also be measured by continuously recording the position of the vehicle on the test course using a 2-dimensional tracking system.

Articulated vehicles may require continuous steering corrections to follow a circular path. In such cases, sufficient data should be obtained to characterize the frequency and amplitude of the necessary steering corrections, as well as the resulting effect on the vehicle parameters that are being measured.

The response time of multi-unit vehicles may be on the order of 10 to 20 s. Vehicle combinations exhibiting this dynamic behavior may not reach a true steady-state condition when operating over imperfect road surfaces; therefore, reaching steady-state during testing may not be feasible.

7. *Data Analysis*

7.1 General—When analyzing the data, the steady-state values for all the measured variables shall be established as the average values of these variables in the elapsed time during which the steady-state was maintained.

The performance limitations of the vehicle noted during testing should be stated. Typical limitations include roll or yaw instability, excessive understeer, or insufficient available power. If wheel liftoff occurs, the wheel location and corresponding lateral acceleration should be recorded.

7.2 Steering Wheel Angle—If the steering wheel angle varied by more than 10 degrees during a test run, the data, if used, shall be so labeled.

7.3 Lateral Acceleration—Steady-state levels of lateral acceleration may be obtained by any one of the following methods:

a. The corrected output of an accelerometer (see 3.2.2).
b. The product of the yaw velocity (corrected for vehicle roll angle) and forward velocity (corrected for sideslip angle).
c. The square of the forward velocity (corrected for sideslip angle) divided by the path radius.
d. The product of the square of the yaw velocity (corrected for roll angle) and the path radius.
e. Calculating "centrifugal" acceleration by measuring the time required for the vehicle to complete one lap of the test course, and correcting for vehicle sideslip angle (see 6.1).

Due to offtracking, each unit of an articulated vehicle may have its own unique level of lateral acceleration. Therefore, if the accelerations acting on the trailing units are of interest, it will be necessary to perform the desired measurements on each unit.

The effect of any test track grade should be considered during the data analysis. For example, the effect of executing a circular turn on a planar surface having a uniform gradient will result in an oscillatory acceleration component being superimposed on the cornering acceleration of the vehicle.

8. *Data Presentation*—General data shall be presented on a summary sheet as shown in Figure B1 in Appendix B. Measured data shall be plotted on figures of Appendix C as follows:

a. Vehicle steering wheel angle data points (see Figure C1).
b. Vehicle sideslip angle data points if measured (see Figure C2).
c. Vehicle roll angle data points if measured (see Figure C3).
d. Steering wheel torque data points if measured (see Figure C4).

For articulated vehicles, graphs of articulation angle versus lateral acceleration and articulation angle versus steering angle may be constructed. "Stick figure" drawings showing the sideslip angle of the towing unit and articulation angles between units are helpful for envisioning the geometry and offtracking of a multi-articulated vehicle performing a steady turn. Tendencies towards jackknifing or trailer swing-out can be noted by examining these figures.

Vehicle directional (yaw) stability may also be characterized on a handling diagram (see Figure C5) by using the vehicle wheelbase, road speed, turn radius, and steering angle data to calculate the necessary data points. For the purpose of constructing handling diagrams, the steering angle (x-coordinate) data points are determined by dividing the steering wheel angle by the steering ratio. The steering ratio is the ratio of the angular movement of the steering wheel to the resulting change of steering angle at the road wheels, with the angle at the steered wheels being an average of the angles assumed by the right and left wheels. Note that steering systems may incorporate variable ratios; in such cases, the appropriate ratio must be applied to each data point.

For vehicles with multi-axle tandems, tridems, belly axles, etc., a handling diagram may be constructed for each velocity used during testing. In these cases, the reference wheelbase is the distance from the centerline of the front axle of the first or towing unit to the geometric center of the rear axles on the first unit. It should be noted that the effective wheelbase of multi-axle vehicles varies with turn geometry and lateral acceleration. While the extent of this variation is generally small, its effect on the handling diagram should be considered during any analysis.

A handling diagram can be used to relate the understeer/oversteer characteristics of a vehicle to lateral acceleration. If the local slope of the curve on the handling diagram is negative for a given lateral acceleration, the vehicle is in an understeering condition. If the slope is positive, the vehicle is in an oversteering condition. Neutral steer is indicated by an infinite slope.

The handling diagram can be used to determine the point of divergent directional instability for a vehicle demonstrating oversteering characteristics. Given a two-axle vehicle (or a two-axle tractor with a single-axle trailer) traveling at a forward velocity V, the vehicle is directionally unstable at lateral acceleration levels for which the local slope of the curve on the handling diagram is less than or equal to the slope of the constant velocity line that corresponds to velocity V (see Figure C6).

Since a handling diagram for multi-axle vehicles consists of a series of curves, each of which is valid only for a specific road speed, the procedure for determining the point of directional instability for multi-axle vehicles must be modified. Directional instability for these vehicles occurs when the slope of the data curve is equal to the slope of the constant velocity line that corresponds to the speed at which the data was taken (see Figure C7). Note that it will be impossible to obtain data that results in a curve with a slope less than the constant velocity line that corresponds to the speed for which the data was taken, since the vehicle will be unstable and not in a steady-state condition.

PREPARED BY THE SAE TRUCK AND BUS SAFETY DYNAMICS SUBCOMMITTEE
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APPENDIX A

DETERMINATION OF OVERALL (STATIC) STEERING RATIO

A.1 The overall steering system ratio shall be determined for each vehicle test configuration over the range of steering wheel angles used during the test. To accomplish this measurement, the steered wheels of the vehicle are first mounted on low-friction bearing pads. The steering wheel angle and the corresponding angles of steer ("wheel cut") at the left and right steered wheels are then measured over a series of steering deflections. It is suggested that these measurements be performed in increments of approximately 2 degrees of wheel cut using protractors or similar devices attached to the steering wheel and the bearing pads. A graph of steering wheel angle versus the mean of left and right steer angles is plotted. From this graph, the mean gradient over the range of steering angles used during testing is determined from each turn direction.

Tilt steering mechanisms can have an effect on the ratio of the steering system. For vehicles with tilt steering, the steering ratio should be determined with the steering set to the same angle that will be used during testing.

The overall steering ratio obtained using this procedure will generally not represent the dynamic situation due to additional steering system deflections caused by compliance and geometric effects. Nevertheless, it is suitable for removing the effect of different steering system lever and gear ratios from comparisons of measurements from different vehicles. The compliance and geometric effects referred to previously are then quite properly regarded as part of the vehicle handling characteristics.

APPENDIX B

GENERAL TEST DATA

Vehicle identification:

	Manufacturer	Year	Model	Type	VIN
Front unit					
Unit 2					
Unit 3					
Unit 4					

Suspension type:

Axle no.	Front unit	Unit 2	Unit 3	Unit 4
1				
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				

Axle geometry:

Axle no.	Location / unit	Track	Distance from no. 1 axle centerline	Steering ratio[a]
1			-------	
2				
3				
4				
5				
6				
7				
8				
9				
10				
11				
12				
13				

[a] Ratio of the angular movement of the steering wheel to the resulting change of steering angle at the road wheels, with the angle at the steered wheels being an average of the angles assumed by the right and left wheels.

FIGURE B1—GENERAL TEST DATA SUMMARY SHEET

Vehicle loading and tire data:

Axle no.	Wheel load Left	Wheel load Right	Tire type Left	Tire type Right	Tire pressure Left	Tire pressure Right
1						
2						
3						
4						
5						
6						
7						
8						
9						
10						
11						
12						
13						

	Front unit	Unit 2	Unit 3	Unit 4	Combination
Total mass					

Center of gravity location:

	Front unit	Unit 2	Unit 3	Unit 4
Vertical, above ground				
Longitudinal, from centerline of unit's lead axle				
Lateral, from longitudinal centerline of unit				

Test conditions:

Test surface description
Weather conditions
Ambient temperature
Wind speed
Test course radii
Sequence of test runs

Test personnel:

Driver
Observers
Data analyst

General comments:

FIGURE B1—GENERAL TEST DATA SUMMARY SHEET (CONTINUED)

APPENDIX C

PRESENTATION OF RESULTS

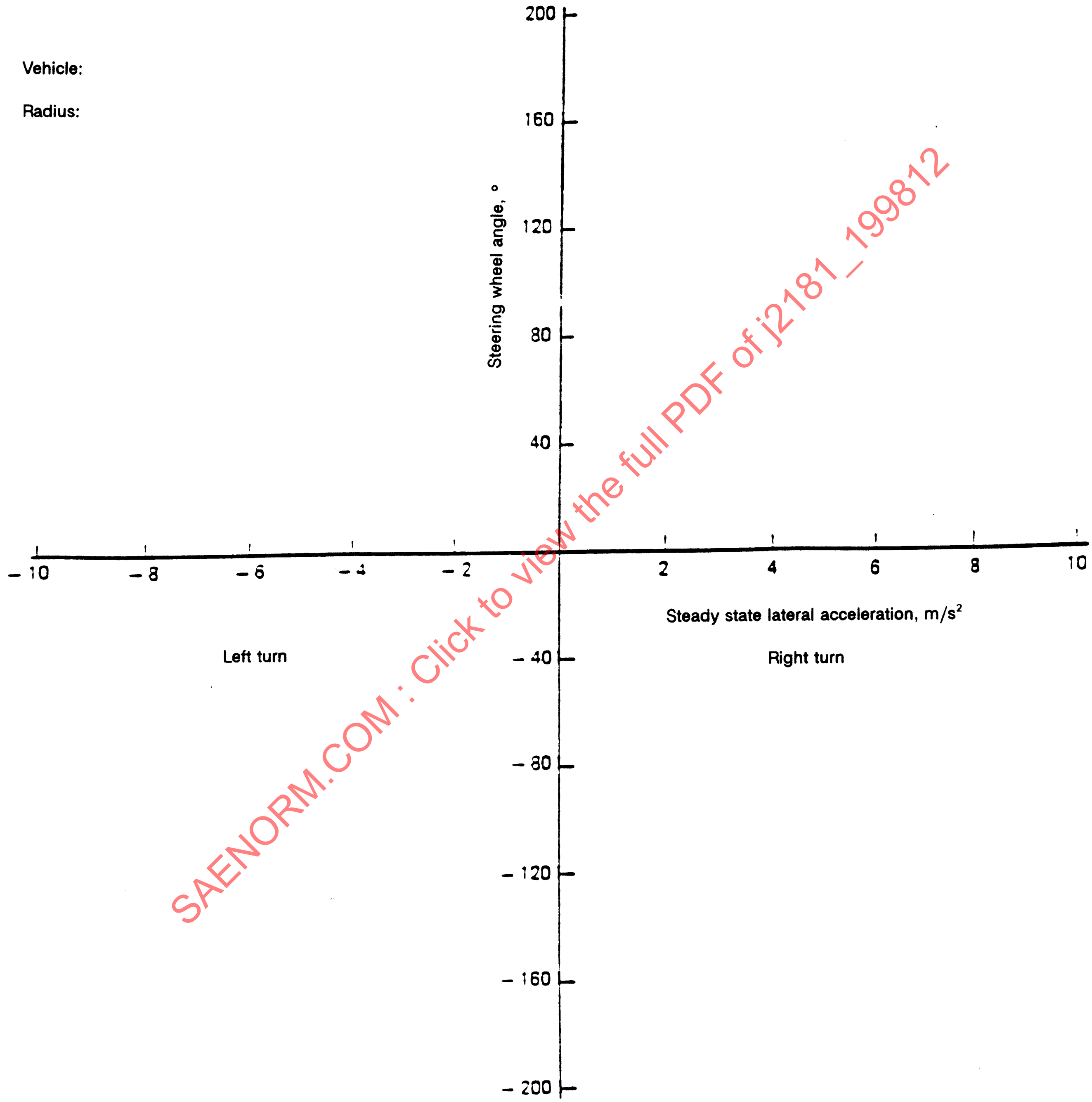

FIGURE C1—STEERING WHEEL ANGLE CHARACTERISTIC

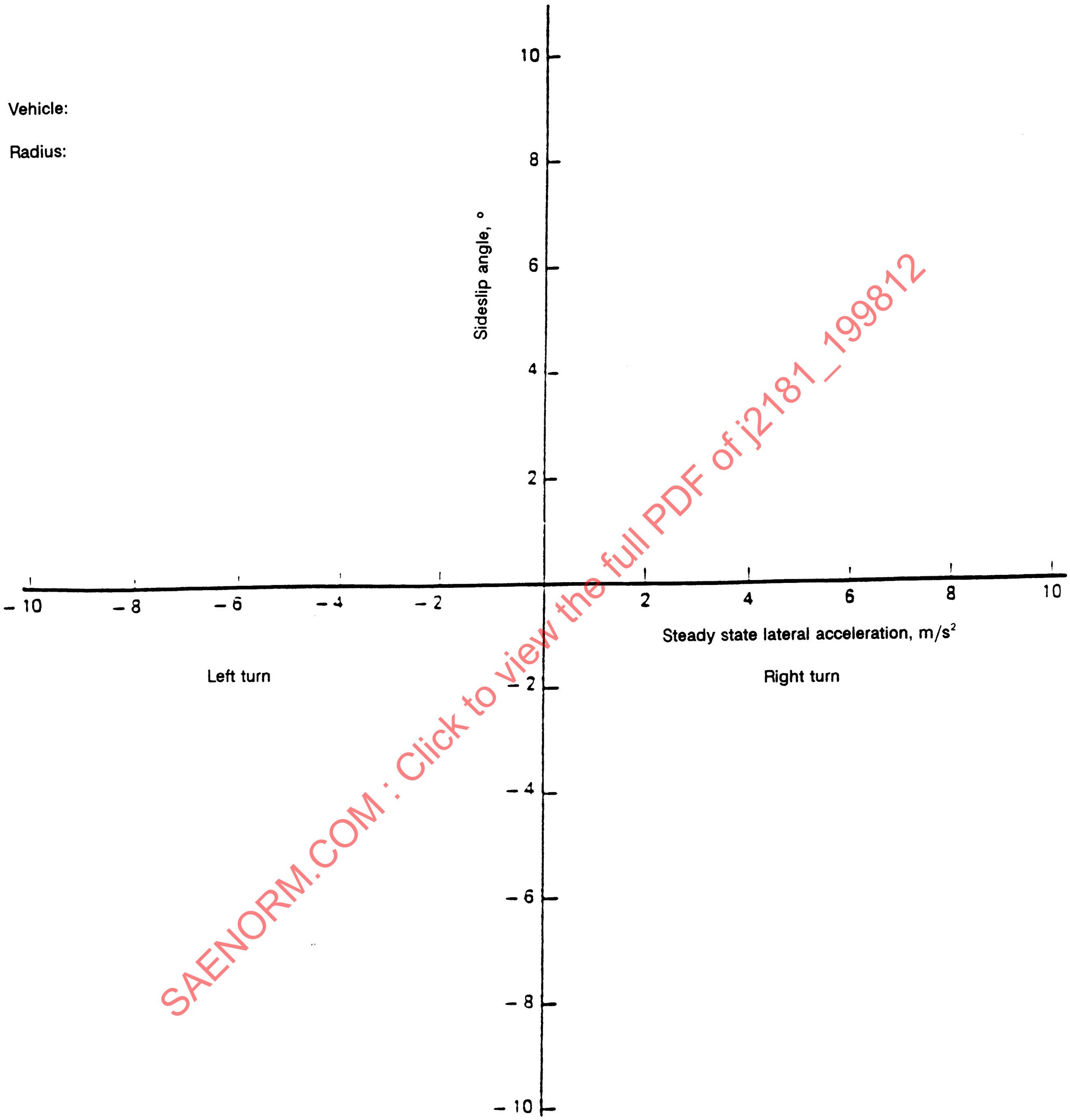

FIGURE C2—SIDESLIP CHARACTERISTIC

Vehicle:

Radius:

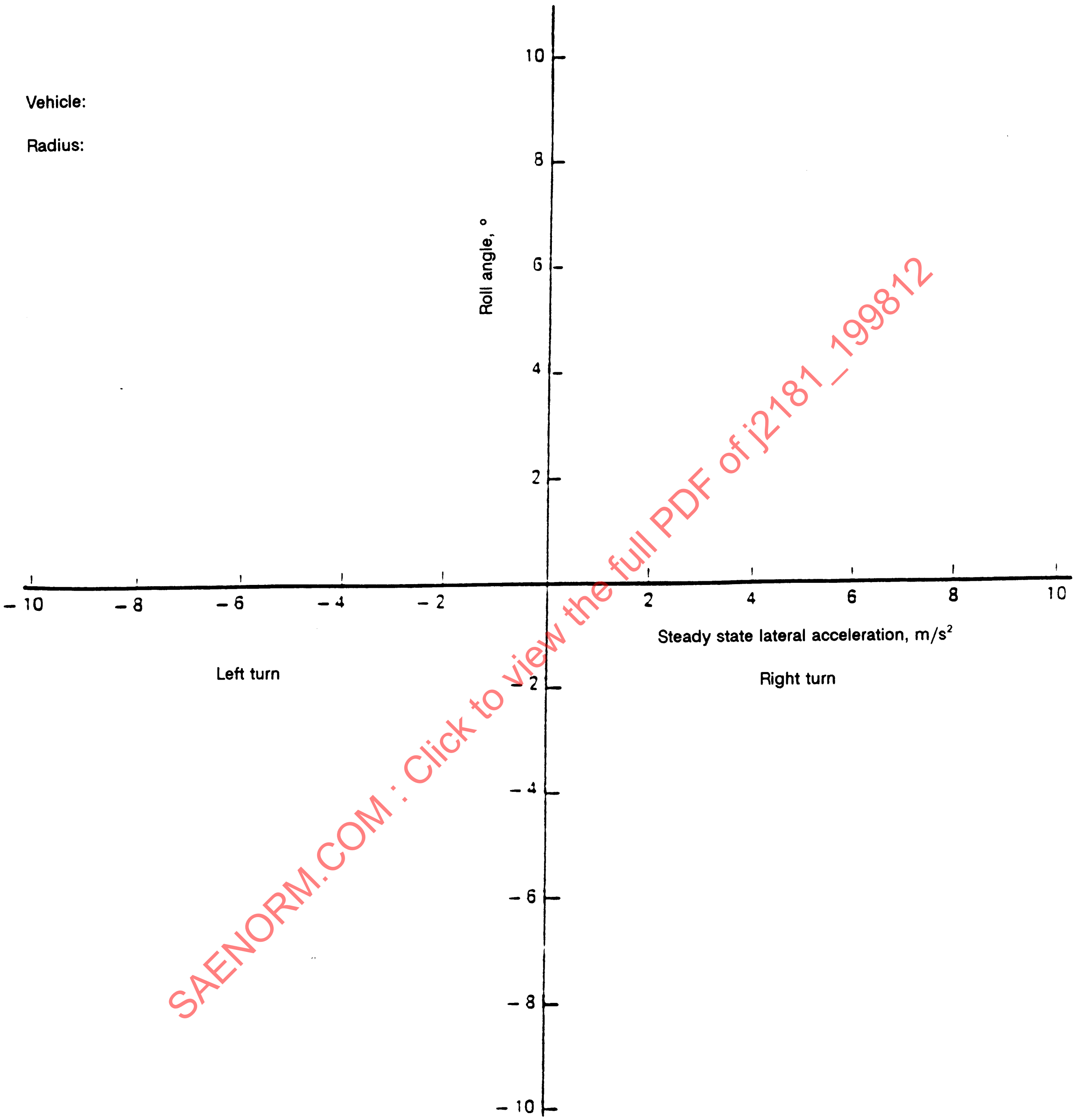

FIGURE C3—VEHICLE ROLL CHARACTERISTIC

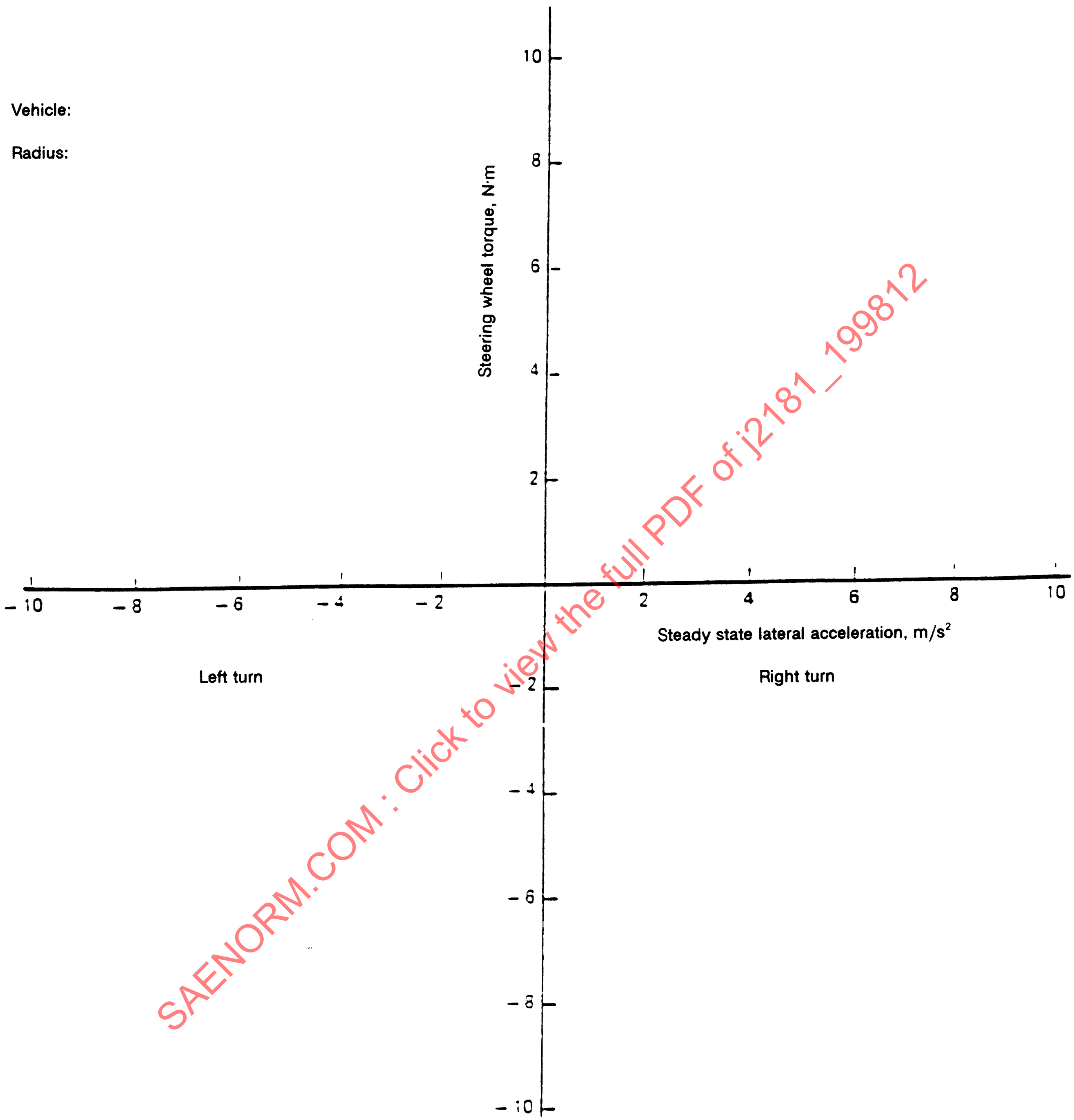

FIGURE C4—STEERING WHEEL TORQUE CHARACTERISTIC