

Driveability Test Maneuver:

Steady-State Circular Test

Objective of the Driving Maneuver

This vehicle dynamics test serves to obtain data to **determine the steady-state behavior of vehicles**. The test is focused on data acquisition of the steering wheel angle as well as the roll and float angle as a function of lateral acceleration in order to enable statements to be made about **self-steering behavior** as well as **comfort evaluation**.

Test Procedures

The steady-state circular test is an **open-loop test** in which either the circular track radius or the steering wheel angle or the vehicle's speed must be constant.

The example shown here involves clock- and counter-clockwise circular tests with a **constant radius of 100 m**, with **increasing vehicle speed**. The tests are driven in second or third gear and lateral accelerations of $a_{quer} = 1 \text{ m/s}^2$ up to the vehicle's driving dynamics limit are set at the typical steps of 1 m/s^2 . During the steady-state trial phase the **steering wheel angle and throttle must be kept constant**.



In each lateral acceleration step the steady-state conditions must be maintained over the measuring period of three seconds and performed three times to demonstrate repeatability and to obtain the average values. The **measurands** (steering angle, roll angle, and others) are plotted over the lateral acceleration. It is recommended to record **tire temperatures** whenever high levels of lateral acceleration prevail during longer trial periods as well. Otherwise, the tires must cool down between the individual tests to ensure comparable conditions.

Alternatively, the steady-state circular test can be performed in such a way that - with continuous data logging - the constant circular radius of 100 m is driven at a slowly increasing speed so that lateral acceleration of $\leq 0.1 \text{ m/s}^2/\text{s}$ increases (**quasi-steady-state circular test**).

Measurands

- Steering wheel angle
- Steering wheel torque
- Lateral acceleration
- Longitudinal acceleration
- Lateral speed
- Longitudinal speed
- Yaw speed
- Float angle
- Trail angle
- Slip angle
- Wheel forces and wheel moments
- Tire temperature

Selection of Measurement Systems to Determine the Relevant Characteristics from the “Steady-State Circular” Vehicle Dynamics Test:

Measurement Steering Wheel MSW

The measurement steering wheel MSW by CORRSYS-DATRON was developed for **simultaneous data acquisition** of the **steering wheel turning angle**, **steering torque** and **steering angle speed**. The steering angle and the steering angle speed derived thereof are obtained by means of a non-contact, optical steering angle sensor. The steering angle can be measured in two measurement ranges ($\pm 200^\circ$ or $\pm 1250^\circ$) at an angular dissolution of 0.05° ; for the steering angle speed, a range of $\pm 1000^\circ/\text{s}$ is available. The measurement steering wheel can be easily fitted to the steering column through a center hole; the assembly depth is relatively small. CORRSYS-DATRON article number: 14256.

Strap-Down Gyro Measuring Device with GPS

The center piece of the ADMA strap-down inertial measurement platform by GeneSys consists of three fiber optic gyros used to **measure the rotational speed** around the x, y and z axis and three accelerometers for the three leveled coordinates. At the same time, the acceleration signals are used to analytically maintain the system in a leveled state by referencing the Earth gravity vector. The gyros enable all angles to be calculated in three dimensions. The major advantages of this system are **high bandwidth** (50...400 Hz), **low data latency** and the provision of all **translational and rotational state parameters** in three space axes, respectively. These are: acceleration, speed, position, rotational speed and angle, which are delivered as output in the onboard, leveled and earth-related coordinates system. With GPS support, drift errors are continually eliminated and with DGPS a **positional accuracy within the range of centimeters** can even be achieved. GeneSys article name: ADMA-G (Automotive Dynamic Motion Analyzer with DGPS).

Pitch and Roll Angle Measurement System

The measurement system is based on the distance measurement of three select vehicle body points vis-à-vis the road. The **pitch angle** θ is the angle between the vehicle's longitudinal axis and its projection to the road, the **roll angle** φ is defined as the angle between the vehicle's transversal axis and its projection to the road.

The θ and φ angles can be calculated as arctan functions from the trigonometric distance relationships. For the speed range of 0 – 250 km/h, the measuring range for the pitch and roll angle is $\pm 40^\circ$ at a resolution of 0.1° .

The HF 500 C height level sensor by CORRSYS-DATRON operates according to the **optical triangulation principle**. A visible red laser is projected onto the object and the reflected light is represented on a CCD line. If the direction of the beam and the distance between the CCD line and the light source are known, the distance between the object and the CCD line can thus be calculated using a signal processor. The distance between the CCD line as well as the two beams from and to the object form a triangle (triangulation).

CORRSYS-DATRON article number: 15380.

Tire Temperature Measurement

A special method, the “**TÜV Tire Temperature Method T³M**”, has been developed to measure the temperature inside the tire structure. The tire temperature is measured with embedded Pt-100 resistance sensors in the tread or tire shoulder. The method specifically pursues the following **objectives**:

- Optimization of the tire in operation
- Thermal analysis and tuning of tire performance and thus vehicle performance.

Using a **telemetry solution** developed by TÜV, the measured data can be transmitted from the rotating wheel to an onboard receiver. As a DTA solution, the thermal stresses for the temperature range between -130°C ... $+179^\circ\text{C}$ are amplified, digitalized and telemetrically transmitted to the stator in the measurement wheel, and forwarded as a LAN protocol to the data acquisition unit. Article name: TÜV-SÜD: T³M (Tire Temperature TÜV SÜD).

Parameters for the Steady-State Circular Test

At increasing vehicle speed the **slip angle difference** between the front and rear axle is of major significance with a one-track model. In case of a positive difference $\alpha_v - \alpha_n$ the steering wheel angle must be increased, in case of negative difference decreased. The **following definitions** have been established:

$\alpha_v - \alpha_n \geq 0$ understeer self-steering effect

$\alpha_v - \alpha_n = 0$ neutral self-steering effect

$\alpha_v - \alpha_n \leq 0$ oversteer self-steering effect

The same definitions apply to the self-steering gradient.

Steady-State Circular Test

In **steady-state driving mode** each axle has to build up lateral forces to support the inertial force $m \cdot a_{quer}$. The axle with the higher slip angle shows greater motion in the lateral direction. In case of **understeer** the higher slip angles occur on the front axle. The vehicle pushes outward over the front axle. When a vehicle **oversteers** the higher slip angles occur on the rear wheels and, in case of high values, can lead to instability.

$$EG = \frac{d\delta_H}{da_{quer}} \cdot \frac{l}{i_s}$$

l = axle distance, i_s = steering ratio

The **self-steering gradient** equates to the incline of the curve $\delta_H = f(a_{quer})$. In the linear vehicle dynamics range up to 4 m/s² the self-steering gradient is a constant, above this value it changes, depending on lateral acceleration.

For yaw speed, the following applies:

$$\frac{\dot{\psi}}{\delta_H} = \frac{v}{i_s \cdot l + i_s \cdot EG \cdot v^2}$$

The **DTA measurement vehicle** has understeering characteristics ($EG > 0$), displaying the typical behavior of yaw intensification initially increasing as speed increases, then reaching a maximum and ultimately decreasing again. The speed equating to the maximum is called characteristic speed.

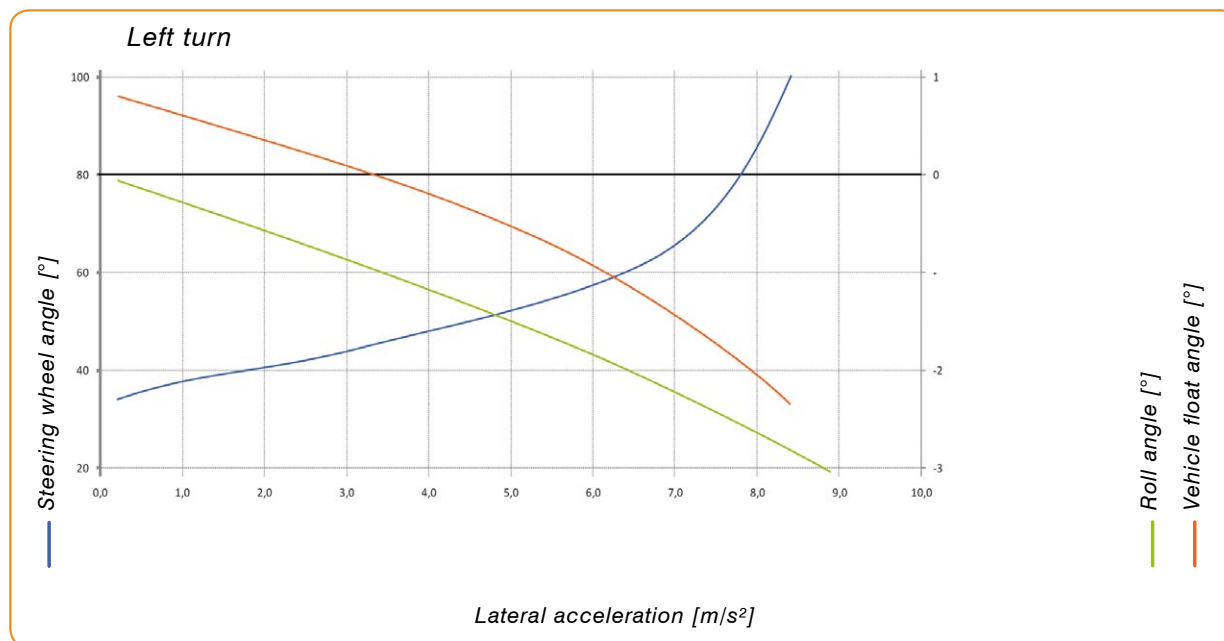
$$v_{ch} = \sqrt{\frac{l^2 \cdot C_v \cdot C_h}{m \cdot (C_h \cdot l_h - C_v \cdot l_v)}}$$

C_v, C_h = slip stiffness front axle, rear axle; l_v, l_h = distances of center of gravity to front axle, rear axle; m = mass

Yaw intensification substantially characterizes the steady-state qualities of a vehicle and is a measure of how intensively the vehicle responds to steering angle changes.

Data Analysis

To analyze the **quasi-steady-state circular test**, TÜV SÜD has developed a routine which, based on existing criteria, serves to identify the respective steady-state conditions set up and to deliver the values for the steering wheel angle and lateral acceleration as averaged values over the measurement period. These individual parameters are plotted using a mathematical interpolation function.



Based on the **positive incline value** of the curve obtained during the counter-clockwise test, for the steady-state range up to 4 m/s^2 , a positive value for the self-steering gradient $EG = 3.35 \frac{\text{rad}\cdot\text{s}^2}{\text{m}}$ is calculated, which means **understeering**. From a lateral acceleration of 5 m/s^2 the amount of steering angle required to maintain the constant cornering radius (100 m) notably increases. At the same time, the steering torque (not plotted here) decreases. The roll angle continually increases with increasing lateral acceleration. The characteristic speed is **112 km/h**.

The **float angle** can be used to characterize the vehicle's orientation relative to its trajectory tangent as well as to evaluate the **vehicle's stability and controllability** up to the limit. In the counter-clockwise test shown here the float angle displays positive values up to a lateral acceleration of 3.5 m/s^2 , which means that the vehicle is oriented toward the outside of the corner with its longitudinal axis. According to the one-track model the float angle has been determined at

$$\beta = \frac{l_h}{R} - \alpha_h$$

l_h = distance between center of gravity and rear axle; α_h = slip angle rear axle

During the **test on a constant radius** the float angle continues to decrease as the slip angle keeps increasing and assumes negative values after a zero crossing. The negative float angle means that the longitudinal vehicle axle now points inward. This behavior does not depend on the self-steering effect but only on the slip angle on the rear axle, which means that understeering vehicles display this characteristic as well.

Summary

The **steering angle characteristic** over the course of the lateral acceleration is an important evaluation criterion for a **vehicle's self-steering behavior**. Its increase in conjunction with increasing lateral acceleration proves the presence of understeering effects. For reasons of vehicle stability and the **safety perception** of the driver, understeering to neutral self-steering characteristics are desirable. The signal curves of the float and roll angles characterize the parameters comfort and safety.

The steady-state circular test is one of the standard tests used to **validate tire models**. The following wheel-related **measurands** depending on lateral acceleration are logged for this purpose: wheel camber angle, slip angle, longitudinal and lateral speed, wheel load, self-aligning and camber torque as well as drive torque. To transform the wheel-related mapping values into the onboard coordinates system, additional measurands are required: longitudinal, lateral and yaw speed, pitch and roll angles as well as wheel travel. The **DTA** is able to provide all of the measurement equipment required for data acquisition of the measurands described above as a **package solution**.

