INTERNATIONAL STANDARD

ISO 19585

First edition
2019-12

Heavy commercial vehicles and buses — Vehicle dynamics simulation and validation — Steady-state circular driving behavior

Véhicules utilitaires lourds et autobus — Simulation et validation dynamique des véhicules — Tenue de route en régime permanent sur trajectoire circulaire

Reference number
ISO 19585:2019(E)

ISO copyright office
CP 401 • Ch. de Blandonnet 8
CH-1214 Vernier, Geneva
Phone: +41 22 749 01 11
Fax: +41 22 749 09 47
Email: copyright@iso.org
Website: www.iso.org

Published in Switzerland

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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For an explanation of the voluntary nature of standards, the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the World Trade Organization (WTO) principles in the Technical Barriers to Trade (TBT) see www.iso.org/iso/foreword.html.

This document was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 33, *Vehicle dynamics and chassis components.*

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

Introduction

The main purpose of this document is to provide a repeatable and discriminatory method for comparing simulation results to measured test data from a physical vehicle for a specific type of test.

The dynamic behaviour of a road vehicle is a very important aspect of active vehicle safety. Any given vehicle, together with its driver and the prevailing environment, constitutes a closed-loop system that is unique. The task of evaluating the dynamic behaviour is therefore very difficult since the significant interactions of these driver–vehicle–environment elements are each complex in themselves. A complete and accurate description of the behaviour of the road vehicle involves information obtained from a number of different tests.

Since this test method quantifies only one small part of the complete vehicle handling characteristics, the validation method associated with this test can only be considered significant for a correspondingly small part of the overall dynamic behaviour.

Heavy commercial vehicles and buses — Vehicle dynamics simulation and validation — Steady-state circular driving behavior

1 Scope

This document specifies a method for comparing simulation results from a vehicle model to measured test data for an existing vehicle according to steady-state circular driving tests as specified in ISO 14792. The comparison is made for the purpose of validating the vehicle model for this type of test.

This document applies to heavy vehicles, including commercial vehicles, commercial vehicle combinations, buses and articulated buses as defined in ISO 3833 (trucks and trailers with a maximum weight above 3,5 tonnes and buses and articulated buses with a maximum weight above 5 tonnes, according to ECE and EC vehicle classification, categories M3, N2, N3, O3 and O4).

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 14792, *Road vehicles — Heavy commercial vehicles and buses — Steady-state circular tests*

ISO 3833, *Road vehicles — Types — Terms and definitions*

ISO 8855, *Road vehicles — Vehicle dynamics and road-holding ability — Vocabulary*

ISO 15037-2:2002, *Road vehicles — Vehicle dynamics test methods — Part 2: General conditions for heavy vehicles and buses*

ISO 19364, *Passenger cars — Vehicle dynamic simulation and validation — Steady-state circular driving behaviour*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 3833, ISO 8855, ISO 15037-2, ISO 19364 and the following apply.

ISO and IEC maintain terminological databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at http://www.electropedia.org/

3.1
simulation
calculation of motion variables of a vehicle from equations in a mathematical model of the vehicle system

3.2
vehicle configuration
fundamental vehicle characteristic influencing the vehicle dynamics

EXAMPLE Number of axles, axle types, number and type of the vehicle units.

Note 1 to entry: An example of axle types can be independent suspension or rigid axle.

3.3
basic vehicle parameters
parameters not subject to model fitting, which are directly and accurately measurable on the test vehicle

EXAMPLE Masses and dimensions.

3.4
estimated vehicle parameters
parameters that may be used for model fitting, which are typically hard to be determined

EXAMPLE Mass moment of inertia and tyre characteristics.

3.5
vehicle model validity range
basic vehicle parameters (3.3) which may be changed if the type of vehicle combination and tyre type are maintained

Note 1 to entry: For example, when wheel base is modified some of the estimated parameters may need to be updated accordingly.

4 Principle

The open-loop test methods defined in ISO 14792 are used to determine the steady-state circular driving behaviour of heavy commercial vehicles and buses as defined in ISO 3833.

Within this document, the purpose of the test is to demonstrate that a vehicle model can predict the vehicle behaviour within specified tolerances. The vehicle model is used to simulate a specific existing vehicle which is also tested physically, using one of the steady-state test methods specified in ISO 14792 for both test and simulation. For single vehicle units, alternatively consider a test with constant vehicle velocity and slowly increasing steer or a test with constant turning radius and slowly increasing vehicle velocity. Measurement results are used to define reference curves and tolerance boundaries, and the respective simulation results are overlaid to analyse the deviation between physical testing and simulation.

The validation process shall be repeated when changing the vehicle configuration, resulting in a fundamental change of the structure of the vehicle model, for example when simulating a three-axle vehicle instead of a two-axle vehicle or when simulating a vehicle combination instead of a single vehicle unit. For one vehicle configuration, it is recommended to repeat the process of comparing simulation and measurement results at least once for a change in basic vehicle parameters, for example for a different loading condition or a different wheelbase, to validate the robustness of the vehicle model.

5 Variables

The variables of motion used to describe the behaviour of the vehicle shall be related to the reference axis system *(X, Y, Z)* of the first vehicle unit (see ISO 8855). For the purpose of this document, the reference point shall be the centre of gravity of the first vehicle unit. This provision overrides the similar provision of ISO 15037-2. Measurement requirements shall be taken from ISO 14792 and ISO 15037-2. The variables that shall be determined for compliance with this document are:

— longitudinal velocity, v_x;

— steering-wheel angle, δ_H;

— lateral acceleration, a_y;

— roll angle of first vehicle unit, φ.

It is recommended that the following variables are also determined:

— steering-wheel torque, M_H;

— yaw velocity, $\dot{\psi}$;

— sideslip angle, β;

— lateral acceleration of the cabin of the first vehicle unit, $a_{y,C}$;

— lateral acceleration of the axles, a_y;

— cabin roll angle of the first vehicle unit, φ_C;

— roll angle(s) of the towed vehicle unit(s) at relevant points, φ_i;

— articulation angle(s) between the vehicle units, $\Delta\psi$.

6 Simulation model parameters and requirements

6.1 General

The vehicle model used to predict the behaviour of a vehicle of interest shall include a mathematical model capable of calculating variables of interest for the test procedures being simulated. In this document, the vehicle model is used to simulate one of the steady-state cornering test methods described in 7.2 and provide calculated values of the variables of interest, see Clause 5.

Any data input into the model should be derived from design data or characteristics measurements of the relevant components described below. If only input data of a similar component are available (e.g. tyre characteristics measurements of tyres of a different brand), the validation process described in this document may serve to identify the unknown component parameters by a parameter variation within moderate, feasible boundaries.

6.2 Basic vehicle parameters — Mass and geometry

The vehicle model shall include all relevant masses of all vehicle units. The value of the mass and the location of the centre of mass are essential properties of the vehicle for the tests covered in this document. Table 1 shows the recommended maximum deviations.

Mathematical models of vehicle combinations shall include a correct representation of the position and the rotational degrees of freedom of the coupling device(s) between the units.

Table 1 — Recommended maximum input data deviation between vehicle model and test vehicle for basic vehicle parameters

Vehicle parameter	Typical usage range	Recommended maximum error between model and physical vehicle combination
Axle and coupling positions with front axle as reference	0 m to 100 m	±0,02 m
Axle loads[a]	0 kg to 15 000 kg	±100 kg
Vehicle unit mass	0 kg to 50 000 kg	±200 kg

[a] To receive an accurate centre of gravity position in the longitudinal direction, each vehicle unit in the vehicle combination with significant vertical force in joint couplings between units, such as fifth wheel on tractor or converter dolly, shall also be measured separately on the weighting scale.

6.3 Estimated vehicle parameters

The following model parameters are based on representative data or calculations with expected variability. As they have substantial influence on the vehicle behaviour during steady-state cornering, they may be adjusted within feasible boundaries for the test vehicle and test conditions during the validation process.

NOTE Moments and products of inertia have no effect under steady-state conditions, when angular accelerations are negligible.

6.3.1 Height of the centre of gravity

For heavy commercial vehicles, the characteristic curve of the roll angle versus lateral acceleration depends largely on the loading condition and the resulting height of the centre of gravity of the vehicle units.

For the purpose of simulation, the height of the centre of gravity of the laden test vehicle can be determined from measurement or design data of the unladen vehicle, modified in accordance with the measured payload geometries and conditions. The loading conditions of the test vehicle shall be recorded as accurately as possible to ensure that the remaining uncertainty in the height of the centre of gravity shall lie within the boundaries shown in Table 2.

NOTE The height of the centre of gravity of the laden vehicle will be influenced not only by the mass and position of the payload but by other associated effects including, but not limited to, suspension and tyre deflections.

6.3.2 Tyre lateral force characteristics

The vertical, lateral, and longitudinal forces and moments where each tyre contacts the ground provide the main actions on the vehicle. The simulated vehicle movement depends largely on the accuracy of the calculated tyre forces and moments.

Large lateral slip angles can occur under the conditions covered in this document. Longitudinal slip ratios are usually limited to the amounts needed to generate longitudinal forces to maintain a target speed in the test. The tyre model should cover the entire ranges of slip (lateral and longitudinal), camber angle relative to the ground, and vertical load that occur in the tests being simulated. The simulated tests may take place on a flat homogenous surface; detailed tyre models that handle uneven surfaces are not needed. The surface friction coefficient between the tyre and ground is an important property for the limit friction conditions that can be encountered in steady-state circular driving tests.

The simulated tests involve conditions that are intended to be steady state; therefore, transient effects in tyre response (e.g. relaxation length) are not relevant.

Typically, the tyre model applied within the vehicle model uses measurements of the tyre characteristics on test rigs as a basis for the tyre model parameters. For the validation, tyre measurements of the same tyres as used on the test vehicle (or, at least, measurements of a tyre with comparable size and wheel load range) shall be used for parametrizing the tyre model. The validation process may be used for adjusting the tyre model parameters within feasible boundaries. It is recommended that (on a dry and even road surface) the deviation of the characteristic curves of the lateral tyre force versus the tyre slip angle used in the tyre model and the curves of the tyre measurement should not exceed ±25 % for slip angles below 10° (see Table 2). To avoid this tolerance being used to alter the balance between front and rear tyre force characteristics, it is recommended that the relative difference between the lateral force characteristics of the tyres at the front axle and the first driven rear axle of the first vehicle unit is not modified by more than 20 % during this adjustment process, see also Table 2. For example, if the cornering stiffness of the tyres of the first axle is increased by 25 %, the cornering stiffness of the rear axle tyres shall also be increased by at least 5 % to meet this requirement. For this comparison of characteristic curves of the tyres, curves of at least three wheel loads should be used, covering a wide range of the wheel loads occurring during the test.

NOTE 1 It can be necessary to consider the tyre side force characteristics for slip angles up to 10° if, during the physical tests, the nonlinear tyre force range is reached.

NOTE 2 When representing the twin tyres on the rear axle of heavy commercial vehicles by a single tyre in the simulation model, the tyre force characteristics of the single tyres are the same as those of twin tyres but the correct track width for twin tyres is parametrized in the model.

6.3.3 Suspension kinematics and compliance properties

The properties of the suspensions that determine how the tyre is geometrically located, oriented, and loaded against the ground shall be represented properly in the vehicle model in order for the tyre model to generate the correct tyre forces and moments. The suspension properties also determine how active and reactive forces and moments from the tyres are transferred to the sprung mass.

The suspension properties should include change of location and orientation of the wheel due to suspension deflection and applied load as would be measured in a physical system in kinematics and compliance (K&C) tests. The K&C properties should not be altered during the validation process.

The vehicle model used for the steady-state cornering tests, shall cover the full range of springs and auxiliary roll moments due to anti-roll bars and other sources of roll stiffness (including the torsional frame stiffness for trucks). Rate-dependent forces such as those produced by shock absorbers are not relevant in steady-state conditions.

During the validation process, the stiffness characteristics of springs and anti-roll bars shall be taken from measurement or design data and should not be altered by more than the corresponding production tolerances of the components, see Table 2.

NOTE 1 The vehicle model can cover the K&C properties either by a measurement-based approach or by detailed suspension modelling. For detailed modelling, the results of K&C simulation and K&C measurement are compared before conducting the entire vehicle simulation. If the vehicle tested for K&C properties is not the same vehicle tested for handling performance, vehicle-to-vehicle variation in suspension geometry and compliance may result in significant differences in K&C properties such as ride, roll, and compliance steer and camber.

NOTE 2 Conventional modelling of leaf springs typically under-represents the amount of auxiliary roll stiffness that leaf spring torsional rate provides.

6.3.4 Steering system

The vehicle model shall include kinematic and compliance relationships (including non-linear effects) between the steering wheel angle and the road wheel angles. Steering system damping and friction are not relevant in steady-state conditions and can be neglected. For compensation of a constant offset between the measured and the simulated curve of the steering wheel angle versus lateral acceleration, the parameters of the steering system giving the overall steering ratio may be adapted to meet the measured curve for low lateral accelerations (see Table 2).

NOTE 1 The steering system geometry can cause different Ackermann steering angles for left- and right-hand steer. This effect is represented correctly in the simulation model.

NOTE 2 Wear in steering system components, particularly a power steering gear, can result in significant changes in steering friction that affect the magnitude and linearity of steering compliance and thereby lateral force and aligning torque compliance steer.

Table 2 — Recommended maximum deviation between initial estimated vehicle parameters and validated estimated vehicle parameters

Estimated vehicle parameter[a]	Recommended maximum variation range
Centre of gravity height	±10 %
Tyre lateral force vs. sideslip angle (for angles <10°)[b]	±25 %
Relative difference of tyre lateral force vs. sideslip angle between front and first driven rear axle of the first vehicle unit[b]	±20 %
Stiffness of suspension components (for first vehicle unit)	±10 %
Overall steering gear ratio (for constant offset)	±5 %

[a] Other model parameters with influence on the driving behaviour during steady-state cornering may also be varied during the validation process.

[b] The tolerances for tyre lateral force mainly serve to compensate for differences between measurements of the tyre characteristics on test rigs and the tyre behaviour on the real road in the physical test status, including tyre wear, tyre temperature, variations in inflation pressure, and others. It is recommended that the simulation use tyre force and moment properties measured on the same make and model tyre(s) with a wear state and date of manufacture similar to those fitted to the test vehicle and at the same tyre pressure(s).

6.4 Additional model requirements

The following model parameters may have additional influence on the vehicle behaviour during steady-state cornering and should therefore be included in the simulation model.

6.4.1 Powertrain

In the steady-state steering manoeuvre, motive power is applied as needed to achieve the vehicle target lateral acceleration. The transfer of drive torque to the wheels should be included in the model, with the proper drivetrain configuration (front-wheel drive, rear-wheel drive, all-wheel drive, electric motors, differentials, etc.).

6.4.2 Chassis stiffness

Vehicles with a significant torsional frame compliance require a representation of this effect, which will influence the definition of the masses of the multibody system.

NOTE 1 The method of attachment of the load platform to the vehicle frame will influence the torsional compliance.

NOTE 2 Frame torsional stiffness and the method of frame restraint in a K&C test affects the measured suspension roll stiffness and to a lesser extent other K&C measurements. Frame compliance acts to reduce the effectiveness of anti-roll bars.

6.4.3 Cabin suspension

For trucks with cabin suspensions, it is recommended that the vehicle model includes a separate mass for the cabin and the characteristics of the springs and anti-roll bars between the chassis and the cabin.

6.4.4 Active braking systems and other active systems

If the brakes are not engaged during the test, the vehicle model does not have to include a representation of the braking system. However, if an active controller engages that uses the brakes to control the vehicle during the steady-state conditions, the vehicle model shall include a representation of the actuators and response properties of the braking system that affect the controlled vehicle response. When the test vehicle is equipped with an ESC rollover stability control, the drivetrain and brake interventions of the system may influence the test results.

Any other electronic controller that engages in the physical vehicle for the steady-state steering manoeuvre should be included in the simulation tool. Physical controllers and/or mechanical components may be linked to the simulated vehicle by hardware-in-the-loop or software-in-the-loop methods. The controller model should include actuators that are not already part of the vehicle brake model and control logic. Examples of other electronic systems influencing the test results are electronically steered rear axles (if acting in the investigated vehicle velocity range) or active roll stability systems such as adjustable anti-roll bar links.

NOTE In case of interventions by an electronic stability control, the vehicle is no longer under steady-state conditions. Therefore, the validation is conducted only for lateral accelerations below the intervention threshold of the system.

6.4.5 Driver Control

The test methods described in 7.2 require control of steering and speed. The vehicle model shall be capable of providing the driver controls (steering, accelerator pedal, cruise control, gear selection) required for the selected test method by including respective lateral and longitudinal controls or a driver model. Alternatively, the steering wheel angle and/or the longitudinal vehicle velocity measured on the vehicle during the physical tests may be used as an input value to the simulation model.

7 Physical tests

7.1 General

An existing vehicle of interest shall be tested using one of the test methods specified below. Unless noted otherwise in this document, the tests shall be conducted and results shall be reported as specified in ISO 14792 and ISO 15037-2. General data of the test vehicle shall be recorded as specified in ISO 15037-2:2002, Annex A. Test conditions of the test vehicle shall be recorded as specified in ISO 15037-2:2002, Annex B. Both the physical tests and the simulations shall be run with clockwise and counter-clockwise steering inputs. For each steering direction, at least three individual valid test runs shall be conducted. For a complete validation, it is recommended to repeat the test with at least one variant of the test vehicle, see Clause 4.

As recommended in ISO 14792, the range of lateral accelerations covered should be as large as is practicable. In each test series, the factor causing the limit condition shall be reported. Usually, for heavy commercial vehicles and buses, the maximum lateral acceleration will be kept significantly lower than the rollover limits of the vehicle unit(s). Thus, the validation may then be limited to the linear region of vehicle dynamics behaviour. For the purpose of this document, lateral acceleration should be measured directly, rather than using the alternative calculation methods provided in ISO 14792.

The vehicle behaviour of interest in this document involves steady state, or quasi steady state, conditions. The low-pass filtering of the variables measured in these tests may use a cut-off frequency lower than those mentioned in ISO 15037-1; the cut-off frequency for the tests used in this document may be as low as 1,0 Hz.

The variables measured in the physical test may need correction in terms of sensor location, orientation, data processing (filtering, etc.) to be comparable to the corresponding simulation signals. Any compensation, for example for lateral acceleration, shall be the same in measurement and simulation and shall be reported.

7.2 Test methods

For heavy vehicle combinations, which require a long time to reach steady-state, one of the two test methods described in ISO 14792 shall be chosen for the validation. Either the constant radius method with constant vehicle velocity, repeating the test for different vehicle velocities, or the constant velocity method with different steering wheel amplitudes may be used. Single vehicle units may use either of these test methods or, alternatively, one of the methods described below. The test method used for both testing and simulation shall be reported.

7.2.1 Constant radius test with slowly increasing velocity

The vehicle is driven on a circular path of known constant radius over a range of lateral acceleration generated with changes in vehicle velocity. The standard radius of the path is 100 m. Larger and smaller radii may be used, with 40 m as the minimum permitted radius. The results depend on the turning radius; therefore, the radius used shall be reported with the test results.

NOTE A larger radius can improve the correlation because influences of the drivetrain are minimized.

From standstill, the vehicle is accelerated slowly until it reaches a chosen level of lateral acceleration or until limits of test space, vehicle speed, or vehicle stability are reached. The lateral acceleration gradient (jerk) shall not exceed 0,2 m/s^3. The steering actions which are necessary to keep the vehicle on the constant radius path shall be applied either by the driver or by a steering robot. The deviation of the path travelled by the vehicle from the constant radius shall not exceed 0,5 m.

7.2.2 Constant speed test with slowly increasing steering wheel angle

The initial condition is driving straight-ahead at a constant vehicle velocity as specified in ISO 15037-2. The results depend on vehicle velocity; therefore, the velocity shall be reported with the test results.

The test is performed at a constant velocity with steering control provided by a robot. From the initial driving condition, the steering wheel angle is increased at a constant rate to run through the desired range of lateral acceleration, or until limits of test space, vehicle speed, or vehicle stability are reached. The lateral acceleration gradient (jerk) shall not exceed 0,2 m/s^3.

7.3 Evaluation of test results

7.3.1 Characteristic curves

The following characteristic curves shall be evaluated for each valid series of tests:

— steering wheel angle versus lateral acceleration;

— roll angle of the first unit versus lateral acceleration.

The following characteristic curves may be evaluated optionally:

— sideslip angle versus lateral acceleration;

— cabin roll angle versus lateral acceleration;

— roll angle(s) of additional vehicle units versus lateral acceleration;

— articulation angle between vehicle units versus lateral acceleration (for vehicle combinations).

7.3.2 Curve fitting

From a series of at least three individual valid test runs, a combined curve shall be determined by an appropriate method of curve fitting. For the curve(s) of the roll angle(s) versus lateral acceleration, it is recommended to use a linear curve fit. For the curve of the steering wheel angle versus lateral acceleration, it is recommended to use a combination of a linear curve fit for the linear region of steering behaviour and a spline curve fit for the nonlinear region (e.g. a cubic spline or a polynomial 3rd order fitting). The method of curve fitting shall be reported.

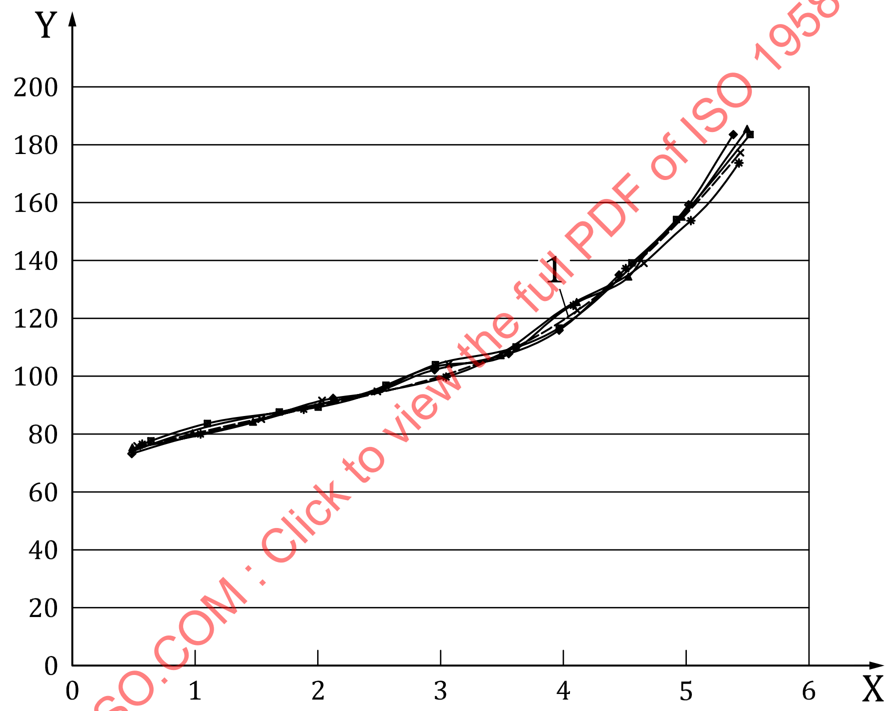
The offset values of the measured variables should be corrected. For the characteristic curve(s) of the roll angle(s), the roll angle should be zero for zero lateral acceleration after the correction. For the characteristic curves of the steering wheel angle and the sideslip angle, the result of the correction should be that the values for zero lateral acceleration in both steering directions correspond to the Ackermann values of the test vehicle for zero lateral acceleration. For determining the Ackermann values see the corresponding formulae given in ISO 8855. For vehicles with three or more axles, the equivalent wheelbase (ISO 8855) may be used to define the Ackermann values.

The combined curve shall be limited to a range of lateral acceleration, where the vehicle is travelling in steady-state conditions and (for the constant radius test with slowly increasing vehicle velocity) with no more deviation from the desired path as specified in 7.2.1. Additionally, it is recommended to use only measurements above a lateral acceleration of 1,0 m/s^2 for curve fitting.

An example for curve fitting from measurement data for curves of the steering wheel angle and the roll angle of the first vehicle unit versus lateral acceleration is shown in Figures 1 and 2.

NOTE 1 The steering geometry can cause different Ackermann steering angles for left- and right-hand turns; in this case a different offset compensation for both steering directions is needed.

NOTE 2 The measured roll angle(s) include additional compensation if measured with respect to the road surface on an inclined road.



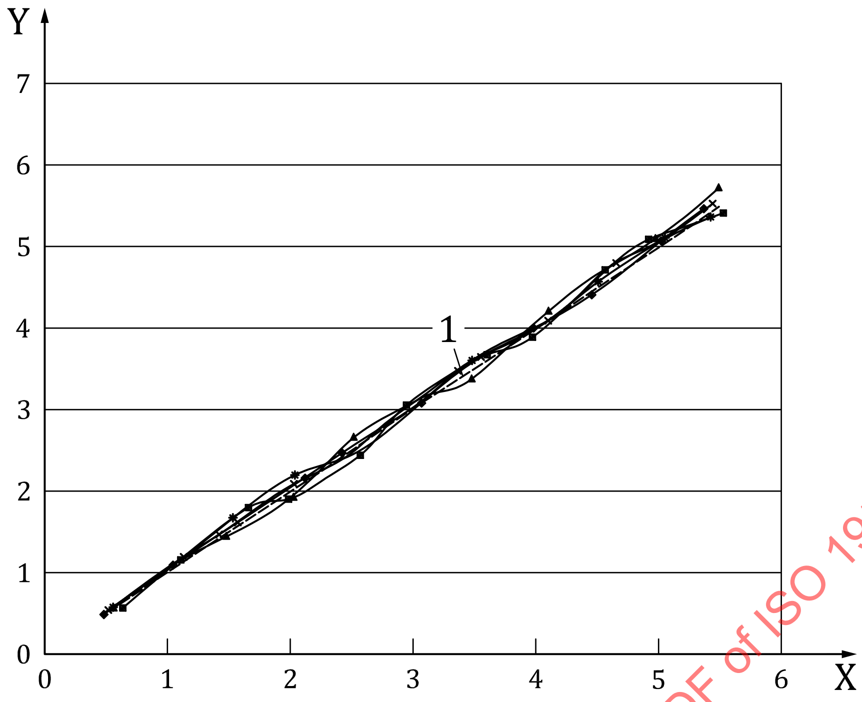
Key

X lateral acceleration [m/s^2]

Y steering wheel angle [°]

1 dashed curve: curve fit from 5 test series

Figure 1 — Example for curve fitting (steering wheel angle versus lateral acceleration)



Key

X lateral acceleration [m/s²]

Y roll angle [°]

1 dashed curve: curve fit from 5 test series

Figure 2 — Example for curve fitting (roll angle versus lateral acceleration)

NOTE 3 For demonstrating the complete curve fit including the nonlinear region, test results of a vehicle with a low centre of gravity position were taken for the example shown. Thus, the range of lateral acceleration covered is bigger than expected for most heavy commercial vehicles and buses.

7.3.3 Gradient values

The following gradient values, as defined in ISO 8855 and ISO 14792, shall be determined:

— Steering-wheel angle gradient;

— Roll angle gradient (from the roll angle of the first vehicle unit).

The following gradient values, as defined in ISO 8855 and ISO 14792, may also be determined:

— Understeer gradient;

— Sideslip angle gradient;

— Cabin roll angle gradient;

— Roll angle gradient(s) of additional vehicle units.

For determination of the gradient values, it is recommended to use a linear curve fit between 1 m/s² and 3 m/s² lateral acceleration. The gradient values may be derived either from the combined curve of the test runs (see 7.3.2) or from a mean value of the gradient values of each of the test runs.

8 Simulation

8.1 General

The simulation shall be conducted with the same test method as used for physical testing and for the same (or larger) range of lateral acceleration. From the simulation, the same characteristic curves and gradient values shall be determined as described in 7.3 for physical testing.

When repeating the process of comparing simulation and measurement results for a change in basic vehicle parameters (e.g. the loading condition or the wheelbase, as recommended in Clause 4), no other than this basic vehicle parameter shall be changed in the simulation tool.

8.2 Data recording

The output of the simulation tool shall have at least the same sampling rate as the recording of the physical tests.

8.3 Documentation

The simulation shall be documented to the extent needed to reproduce the simulated tests. This shall include at least:

- test method and corresponding test conditions used for validation;
- name and version number of the vehicle model;
- name and version number of the tyre model;
- internal name of the vehicle model;
- list and contents of input files used;
- list and version numbers of active control systems connected as hardware-in-the-loop or software-in-the-loop elements.

9 Comparison of simulation and physical tests

9.1 Documentation

The averaged curves evaluated from the measurement data described in 7.3 are used to calculate the upper and lower boundaries employed for validation of the simulation results. Alternatively, the simulation model may be used to predict the upper and lower test boundaries, as specified in ISO 19364, in advance of a physical test.

In contrast to ISO 19364 the offset values are not used to define the tolerance boundaries. Consequently, it is necessary to adjust the measurement results to give the correct offset values at zero lateral acceleration (e.g. set the steering wheel angle offset corresponding to the correct Ackermann steer condition and zero the roll angle). Accordingly, the tolerance boundaries defined in this standard shall commence at the lateral acceleration values specified in 9.2 below.

9.2 Calculation of boundary points

Given a set of lateral acceleration values associated with the X axis and a set of values of another variable associated with the Y axis, the X and Y coordinates for the top boundary are given by Formulae (1) and (2):

$$X_T = X - \Delta Y \, \varepsilon_x^2 / D \tag{1}$$

$$Y_T = Y + \Delta X\, \varepsilon_y^2 / D \qquad (2)$$

The X and Y coordinates for the bottom boundary are given by Formulae (3) to (5):

$$X_B = X + \Delta Y\, \varepsilon_x^2 / D \qquad (3)$$

$$Y_B = Y - \Delta X\, \varepsilon_y^2 / D \qquad (4)$$

where

$$D = \sqrt{[(\Delta X\, \varepsilon_y)^2 + (\Delta Y\, \varepsilon_x)^2]} \qquad (5)$$

ΔX is the difference between the X-axis variable (a_y) for the current value and preceding value;

ΔY is the difference between the Y-axis variable (e.g. steering wheel angle δ_H) for the current value and preceding value;

ε_x is the tolerance for the lateral acceleration;

ε_y is the tolerance for the Y-axis variable.

The tolerances ε_x and ε_y for each cross plot are calculated using a gain factor with Formulae (6) and (7):

$$\varepsilon_x = [X\ \text{gain}] \times |X| \qquad (6)$$

$$\varepsilon_y = [Y\ \text{gain}] \times |Y| \qquad (7)$$

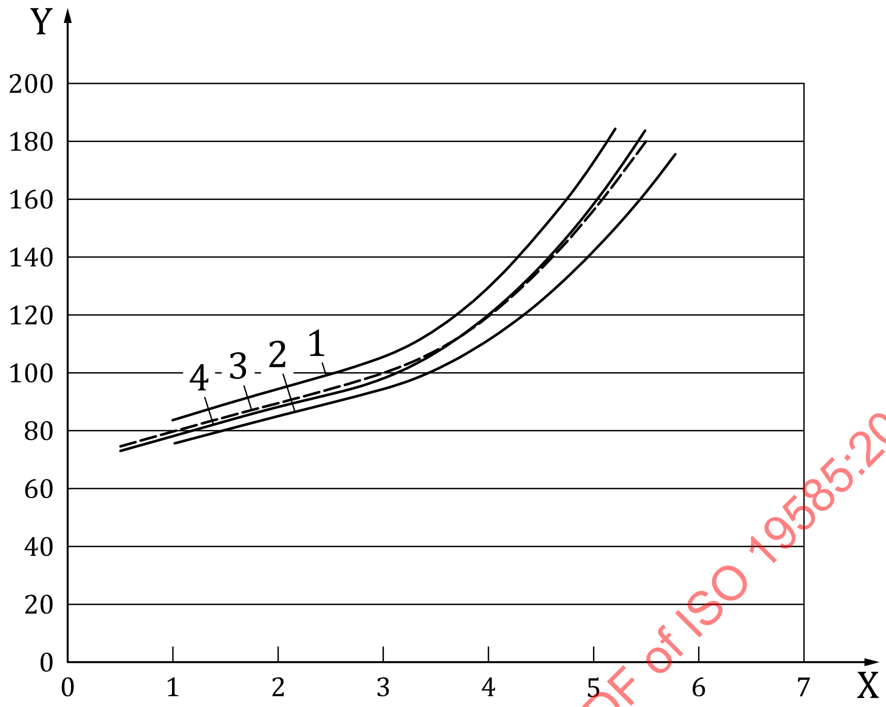
Recommended gains for proving good correlation between physical testing and simulation are listed in Tables 3 and 4. If the individual physical test results are outside the calculated boundaries, the gain factors should be adjusted.

Table 3 — Gains used to define tolerances ε_x and ε_y

Variable on *Y* axis	*X* gain	*Y* gain
Steering wheel angle (°)	0,06	0,05
Roll angle (°)	0,06	0,08
Side slip angle (°)	0,06	0,05
Articulation angle (°)	0,06	0,05

An example for the top and bottom boundaries of the characteristic curves of the steering wheel angle and the roll angle versus lateral acceleration is shown in Figures 3 and 4, for the same example as Figures 1 and 2.

In accordance with the curve fitting requirements for the physical measurement results described in Clause 7, the simulation tolerance boundaries are recommended to be applied in the region above 1,0 m/s^2 (minimum 0,5 m/s^2) as the measurement results are usually relatively inaccurate, and can be influenced by offsets (see 9.1), at very low lateral accelerations.



Key

X lateral acceleration [m/s²]

Y steering wheel angle [°]

1 upper boundary

2 lower boundary

3 dashed curve: curve fit from 5 test series

4 lined curve: simulation

Figure 3 — Example for boundaries, steering wheel angle