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Passenger cars — Validation of vehicle dynamics simulation — Lateral transient response test methods

Voitures particulières — Validation de la simulation de la dynamique du véhicule — Méthodes d'essai de réponse transitoire latérale

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Foreword

ISO (the International Organization for Standardization) is a worldwide federation of national standards bodies (ISO member bodies). The work of preparing International Standards is normally carried out through ISO technical committees. Each member body interested in a subject for which a technical committee has been established has the right to be represented on that committee. International organizations, governmental and non-governmental, in liaison with ISO, also take part in the work. ISO collaborates closely with the International Electrotechnical Commission (IEC) on all matters of electrotechnical standardization.

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 .org/directives).

Attention is drawn to the possibility that some of the elements of this document may be the subject of patent rights. ISO shall not be held responsible for identifying any or all such patent rights. Details of any patent rights identified during the development of the document will be in the Introduction and/or on the ISO list of patent declarations received (see www .org/patents).

Any trade name used in this document is information given for the convenience of users and does not constitute an endorsement.

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 .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 .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 necessarily 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.

Passenger cars — Validation of vehicle dynamics simulation — Lateral transient response test methods

1 Scope

This document specifies methods for comparing computer simulation results from a vehicle mathematical model to measured test data for an existing vehicle according to ISO 7401. The comparison is made for the purpose of validating the simulation tool for this type of test when applied to variants of the tested vehicle.

It is applicable to passenger cars as defined in ISO 3833.

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 1176:1990, *Road vehicles — Masses — Vocabulary and codes*

ISO 2416, *Passenger cars — Mass distribution*

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

ISO 7401:2011, *Road vehicles — Lateral transient response test methods — Open-loop test methods*

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

ISO 15037-1:2019, *Road vehicles — Vehicle dynamics test methods — Part 1: General conditions for passenger cars*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 1176, ISO 2416, ISO 3833, ISO 8855 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 .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
simulation tool
simulation (3.1) environment including software, model, input data, and hardware in the case of hardware in the loop simulation

4 Principle

Open-loop test methods specified in ISO 7401 are used to determine the lateral transient response of passenger cars in time and frequency domain as defined in ISO 3833.

In time domain:

— step input;

— sinusoidal input (one period).

In frequency domain:

— random input;

— pulse input;

— continuous sinusoidal input.

The test characterizes transient response behaviour of a vehicle. Characteristic values and functions in time and frequency domains are considered necessary for characterizing vehicle transient response.

Important characteristics in time domain are

— time lags between steering-wheel angle, lateral acceleration and yaw velocity,

— response times of lateral acceleration and yaw velocity,

— lateral acceleration gain (lateral acceleration divided by steering-wheel angle),

— yaw velocity gain (yaw velocity divided by steering-wheel angle), and

— over-shoot values.

Important characteristics in frequency domain are the frequency responses, i.e. amplitudes and phases of:

— lateral acceleration related to steering-wheel angle;

— yaw velocity related to steering-wheel angle.

Within this document, the purpose of the test is to demonstrate that a vehicle simulation tool can predict the vehicle behaviour within specified tolerances. A vehicle simulation tool is used to simulate a specific existing vehicle running through the open-loop tests specified in ISO 7401.

The existing vehicle is physically tested at least three times to allow the test data to be compared with the simulation results.

For time domain, response comparison is made between measured and simulated characteristic values using tolerances of percent errors specified in this document.

For frequency domain, response comparison is made between measured and simulated characteristic functions of amplitudes and phases using tolerances specified in this document. Simulation results are used to define boundaries for frequency response curves, and the data from physical testing are overlaid to see if the measurements fall within the acceptable ranges.

NOTE 1 This document can be used for different purposes. Depending on the purpose of the validation, only parts of the validation requirements can be met.

NOTE 2 Tolerance requirements can differ for applications, thus different tolerance values can be agreed between parties involved depending on the applications.

5 Variables

The following variables shall be measured from physical testing, and applying the measured steering-wheel angle and longitudinal velocity as simulation input, yaw velocity and lateral acceleration are computed:

- steering-wheel angle, δ_H;
- yaw velocity, $\dot{\psi}$;
- lateral acceleration, a_Y;
- longitudinal velocity, v_X.

The following optional variables may be measured from physical testing, and obtained from a simulation tool:

- roll angle, ϕ ;
- sideslip angle, β;
- lateral velocity, v_Y;
- steering-wheel torque, M_H.

6 Simulation tool requirements

6.1 General

The simulation tool used to predict behaviour of a vehicle of interest shall include a mathematical model capable of calculating variables of interest (see Clause 5) for the test procedures being simulated. In this document, the mathematical model is used to simulate an open-loop test series as specified in ISO 7401 and provide calculated values of the characteristic variables and functions of interest.

The simulation tool shall be able to cover the lateral acceleration level of time domain tests where lateral acceleration value starts from the nominal value of 4,0 m/s^2.

The procedure for obtaining input data from experiments may differ for simulation tools, however, the input data shall not be manipulated for better correlation. Nonetheless, adaptation of input data to actual testing conditions such as road friction should be allowed.

6.2 Mass and inertia

The mathematical model should include all masses, such as the chassis, engine, payloads, unsprung masses, etc. The value of the mass, the location of the centre of mass, and moments and products of inertia are essential properties of the vehicle for the tests covered in this document.

Vehicles with significant torsional frame compliance require a more detailed representation that includes frame-twist effects that occur in extreme manoeuvres.

6.3 Tires

The vertical, lateral, and longitudinal forces and aligning and overturning moments where each tire contacts the ground provide the main actions on the vehicle. The fidelity of the prediction of vehicle movement depends on the fidelity of the calculated tire forces and moments. Differences between the tire force and moment measurements used for the model and those used in vehicle testing can be expected due to different wear and aging histories. Although it is difficult to account for these differences, it is important to acknowledge and understand them.

Large lateral slip angles and camber angles can occur under the conditions covered in this document. The tire model shall cover the entire range of slip (lateral and longitudinal), inclination angle relative to the ground, and load that occur in the tests being simulated. The tire lateral force reduction at high slip angles is a critical characteristic that shall be comprehended by the tire testing and modelling. The effect of combined tire lateral and longitudinal slip on forces and moments shall also be modelled.

The surface friction coefficient between the tire and ground is an important property for the limit friction conditions that can be encountered in tests.

The simulated tests take place on a flat homogenous surface; detailed tire models that handle uneven surfaces are not needed. If the test surface has inclination for water drainage, this should be included in the simulation.

6.4 Suspensions

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

The suspension properties should include change of location and orientation of the wheel due to suspension vertical deflection, steering, and compliance due to applied load as would be measured in a physical system in kinematics and compliance (K&C) tests.

The model shall cover the full nonlinear range encountered in the tests for springs, jounce and rebound bumpers, and auxiliary roll moments due to anti-roll bars and other sources of roll stiffness.

Rate-dependent forces such as shock absorbers are significant and shall cover the range of suspension jounce and rebound rate encountered in the tests.

6.5 Steering system

The steering system interacts with the suspensions to determine how the tire is oriented on the ground.

The test requires that either a robot or driver provides steering wheel control. The model should include kinematical and compliance relationships needed to calculate the road wheel angles from the steering-wheel angle.

The model should include the effects of active control systems, if applicable in the test.

If a robot controller provides the steering, the model does not need to predict the associated steering-wheel torque for this document. However, it should be recognized that inadequate steering robot torque capacity can result in steering inputs that do not match the intended angle. This can be a source of discrepancy between simulation and test results.

6.6 Aerodynamics

The model should include aerodynamic effects that influence tire load and overall vehicle drag for speeds up to 120 km/h.

6.7 Brake system

If the brakes are not engaged during the testing, then the brake system is not needed. However, if an active controller engages that uses the brakes to control the vehicle during the test covered in this document (see 6.9), then the vehicle brake model shall include the actuators and response properties that affect the controlled vehicle response.

6.8 Powertrain

In the open-loop steering manoeuvre covered in this document, the standard speed is 100 km/h, and other test speeds of interest may be used (preferably in 20 km/h steps). The model should include the drag on the driven wheels, as needed to replicate this behaviour. Inertial effects that influence the wheel spin dynamics during any intervention by active control system shall be included.

Other aspects of powertrain behaviour that are important for other kinds of tests (engine power, dynamic responses to throttle, shifting and clutch behaviour) are probably not needed for constant speed of the tests; however, if a chassis control system engages, then any aspects of the powertrain that influence the controller behaviour shall be included in the powertrain model.

6.9 Active control system (ESC system, active roll control, etc.)

Any electronic control system that engages in the physical vehicle for the open-loop test manoeuvre covered in this document shall be included in the simulated version.

Physical controllers and/or mechanical components may be linked to the simulated vehicle by hardware in the loop.

The control system model shall include actuators that are not already part of the vehicle brake model (see 6.7), transfer delays, and control logic.

The transmission behaviour of the signal quality and the time delay should be included in the model.

6.10 Data acquisition

Procedures for extracting signals from the simulation should mimic the procedures used to obtain signals from the physical vehicle for the variables listed in Clause 5. For example, sensor location, orientation, data processing including filtering, in the simulation should match the physical test setup.

6.11 Driver controls

The test methods described in Clause 7 require control of steering and speed. The simulation tool shall be capable of applying the driver controls (steering, throttle, gear selection) measured from the selected test method.

7 Physical testing

7.1 General

An existing vehicle of interest shall be tested using test procedures specified in ISO 7401, where five test methods are defined; step input and one period sinusoidal input test for time domain, and random input, pulse input, and continuous sinusoidal input test for frequency domain. These test methods are optional, but at least one of each domain type shall be performed.

NOTE This document does not define all the details of the testing procedure. Clause 7 describes the parts of the test procedure that are typically simulated.

7.2 Measuring equipment

Specification for measuring equipment, installation and data processing shall be in accordance with ISO 7401:2011, Clause 8.

7.3 Test conditions

General test conditions shall be in accordance with ISO 7401:2011, Clause 9.

Tests shall be carried out with the design loading condition where the total vehicle mass shall consist of the complete vehicle kerb mass (code: ISO-M06) in accordance with ISO 1176:1990, 4.6, plus the masses of the driver and the instrumentation. The mass of the driver and the instrumentation shall not exceed 150 kg. The load distribution shall be equivalent to that of two occupants in the front seats, in accordance with ISO 2416. (see ISO 7401:2011, 9.2.2).

NOTE ISO 7401 requires testing with both the design and maximum loading conditions. However, since minimum loading condition represents more realistic driving situation, validation is performed with the design loading condition.

The warm-up procedures specified in ISO 15037-1:2019, 6.1 shall apply.

The test speed is defined as the nominal value of the longitudinal velocity. The standard test speed is 100 km/h. Other test speeds of interest may be used (preferably in 20 km/h steps).

7.4 Filtering of measured data

Raw measurements of steering-wheel angle, yaw velocity, lateral acceleration, longitudinal velocity, and other optional variables shall be filtered and conditioned as specified in ISO 15037-1.

7.5 Test methods

7.5.1 Step input

7.5.1.1 Test procedure

Test procedure specified in ISO 7401:2011, 10.1 shall apply. Take data for both left and right turns. All data shall be taken in one direction followed by all data in the other direction. Alternatively, take data successively in each direction for each acceleration level, from the lowest to the highest level, this being preferable with respect to tyre wear and symmetrical vehicle stress. Record the method chosen in the test report (see ISO 7401:2011, Annex A).

Perform all test runs at least three times.

7.5.1.2 Data analysis

Response time, peak response time, and overshoot values specified in ISO 7401:2011, 10.2 shall be calculated.

ISO 7401 does not specify how to determine peak or steady-state values. One method to determine steady-state values would be averaging for 3 s after steady-state is estimated to be reached. Method used for measured data shall be applied to simulated data.

7.5.1.3 Data presentation

General data shall be presented in accordance with ISO 7401:2011, Annex A.

The time histories of steering-wheel angle, lateral acceleration, yaw velocity, and longitudinal velocity, as shown in ISO 7401:2011, Figure B.1, shall be plotted. If a curve is fitted to any set of data, the method of curve fitting shall be described in the presentation of results in ISO 7401:2011, Annex B.

Record the following values in accordance with ISO 7401:2011, Table B.1 for each combination of test speed and lateral acceleration:

— steady-state yaw velocity response gain, $\left(\frac{\dot{\psi}}{\delta_{\mathrm{H}}}\right)_{\mathrm{ss}}$;

— lateral acceleration response time, T_{a_Y};

— yaw velocity response time, $T_{\dot{\psi}}$;

— lateral acceleration peak response time, $T_{a_{Y\max}}$;

— yaw velocity peak response time, $T_{\dot{\psi}_{\max}}$;

— overshoot value of lateral acceleration, U_{a_Y} ;

— overshoot value of yaw velocity, $U_{\dot{\psi}}$.

7.5.2 Sinusoidal input — One period

7.5.2.1 Test procedure

Test procedure specified in ISO 7401:2011, 11.1 shall apply. Take data both to the left and to the right. All data shall be taken in one direct followed by all data in the other direction. Alternatively, take data successively in each direction for each acceleration level, from the lowest to the highest level. Record the method chosen in the test report (see ISO 7401:2011, Annex A).

Perform all test runs at least three times.

7.5.2.2 Data analysis

Lateral acceleration, yaw velocity, time lags, lateral acceleration gain, yaw velocity gain specified in ISO 7401:2011, 11.2 shall be calculated.

ISO 7401 does not specify how to determine characteristic values. Method used for measured data shall be applied to simulated data.

7.5.2.3 Data presentation

General data shall be presented in accordance with ISO 7401:2011, Annex A.

The time histories of variables used for data evaluation shall be plotted. If a curve is fitted to any set of data, the method of curve fitting shall be described in the presentation of results in accordance with ISO 7401:2011, Annex B.

Plot the time history of steering-wheel angle, lateral acceleration and yaw velocity for each measured lateral acceleration level as shown in ISO 7401:2011, Figure B.2.

Calculate the following test data (see ISO 7401:2011, Table B.2):

— time lags between steering-wheel angle and lateral acceleration;

— first peak, $T_{(\delta_H - a_Y)_1}$;

— second peak, $T_{(\delta_H - a_Y)_2}$;

— time lags between steering-wheel angle and yaw velocity;

 — first peak, $T_{(\delta_H - \dot{\psi})_1}$;

 — second peak, $T_{(\delta_H - \dot{\psi})_2}$;

— lateral acceleration gain, $\frac{a_Y}{\delta_H}$;

— yaw velocity gain, $\frac{\dot{\psi}}{\delta_H}$.

7.5.3 Random input

7.5.3.1 Test procedure

Test procedure specified in ISO 7401:2011, 12.1 shall apply. To ensure enough total data, capture at least 12 min of data, unless confidence limits indicate that a shorter time is sufficient. Ideally, all data should be accomplished in a continuous run, however data may be captured using a number of shorter runs of at least 30 s duration.

7.5.3.2 Data analysis

The data processing can be carried out using a multi-channel real time analyser or a computer with the appropriate software.

Preliminary analysis for steering-wheel angle time history shall be performed as specified in ISO 7401:2011, 12.2.2 and result shall be displayed as graph of the input level relative to that at the lowest frequency versus frequency, as shown in ISO 7401:2011, Figure B.3.

This graph shall be examined to ensure adequate frequency contents. The recommended ratio between the maximum and minimum steering-wheel angle should be not greater than 4:1 (12 dB). If this ratio is greater, the results may be discarded or, if used, the extent of the ratio shall be recorded in the test report (see ISO 7401:2011, Figure B.3).

The data shall then be processed using equipment appropriate for producing the transfer function amplitude and phase information together with the coherence function for the following combinations of input and output variables:

a) lateral acceleration related to steering-wheel angle;

b) yaw velocity related to steering-wheel angle.

If data has not been captured in a continuous run, calculate the auto and cross-spectral densities for each run. The results of individual runs shall then be averaged. The averaging function used shall be recorded in the test report (see ISO 7401:2011, Annex A).

7.5.3.3 Data presentation

General data shall be presented in accordance with ISO 7401:2011, Annex A.

For each pair of input and output variables, the frequency response (i.e. gain and phase angle functions) shall be presented on a graph as shown in ISO 7401:2011, Figure B.4. The figure shall be completed with the number and length of the data sequences, the averaging function, the digitizing rate and the windowing function used.

The coherence function shall also be presented on the graph (see ISO 7401:2011, Figure B.4). This coherence function quantifies the amount of correlated information in relation to noise present in the data. To obtain close confidence limits, it is necessary to have high coherence levels and a large number of averages.

Experience shows that coherence for yaw velocity related to steering-wheel angle shall be above 0,95 in the range from 0,2 to 2 Hz for reproducible and reliable test results.

7.5.4 Pulse input

7.5.4.1 Test procedure

The test procedure specified in ISO 7401:2011, 13.1 shall apply. Perform all test runs at least three times.

7.5.4.2 Data analysis

The preliminary analysis for steering-wheel angle time history shall be performed as specified in ISO 7401:2011, 13.2.2 and results shall be displayed as graph of the input level relative to that at the lowest frequency versus frequency, as shown in ISO 7401:2011, Figure B.3.

The data shall then be processed using equipment appropriate for producing the transfer function amplitude and phase information together with the coherence function for the following combinations of input and output variables:

a) lateral acceleration related to steering-wheel angle;

b) yaw velocity related to steering-wheel angle.

The transfer functions of at least three test runs shall be averaged.

7.5.4.3 Data presentation

General data shall be presented in accordance with ISO 7401:2011, Annex A.

Time histories of variables used for data evaluation shall be plotted. If a curve is fitted to any set of data, the method of curve fitting shall be described in the test report in accordance with ISO 7401:2011, Annex B.

For each pair of input and output variables, the frequency response (i.e. gain and phase-angle functions) shall be presented on a graph, as shown in ISO 7401:2011, Figure B.4. The graph shall be completed with the number and length of the data sequences, the averaging function, the digitizing rate and the windowing function used.

The coherence function shall also be presented on the graph (see ISO 7401:2011, Figure B.4). This function quantifies the amount of correlated information in relation to noise present in the data. To obtain close confidence limits, it is necessary to have high coherence levels and a large number of averages.

7.5.5 Continuous sinusoidal input

7.5.5.1 Test procedure

The test procedure specified in ISO 7401:2011, 14.1 shall apply.

7.5.5.2 Data analysis

Amplitude of steering wheel angle, lateral acceleration and yaw velocity is defined as the mean value of the amplitudes following the first period.

All amplitudes shall be taken during the manoeuvre when the vehicle is in a periodic steady-state condition.

Lateral acceleration gain (see ISO 7401:2011, 14.2.2), yaw velocity gain (see ISO 7401:2011, 14.2.3), and phase angle (see ISO 7401:2011, 14.2.4) shall be calculated in accordance with ISO 7401.

Phase angles between the steering-wheel angle and the lateral acceleration and yaw velocity shall be determined from the time histories after the first period, when the vehicle is in a periodic steady-state condition.

7.5.5.3 Data presentation

General data shall be presented in accordance with ISO 7401:2011, Annex A.

Time histories of variables used for data evaluation shall be plotted. If a curve is fitted to any set of data, the method of curve fitting shall be described in the test report in accordance with ISO 7401:2011, Annex B.

For each pair of input and output variables, the frequency response (i.e. gain and phase-angle functions) shall be presented on a graph, as shown in ISO 7401:2011, Figure B.4.

8 Simulation

8.1 General

The simulation tool shall be configured to simulate the methods in Clause 7 that were chosen to physically test the existing vehicle. Because the computer simulations might not be sensitive to some factors of interest in physical testing, not all of the details specified in ISO 7401 and ISO 15037-1 apply. Requirements from ISO 7401 and ISO 15037-1 for repeated tests, warm-up, transducer properties, filtering, etc. might be irrelevant. Factors that do not affect the simulations may be neglected to reduce the number of simulations or simplify the data processing.

8.2 Data recording and processing

The purpose of each test is to obtain values and functions in time and frequency domain. These values and functions shall be extracted from the simulation tool and written to file such that they can be used to calculate characteristic values.

Extracted variables shall be filtered with the same method used for measured data as in 7.4.

8.3 Simulation method

8.3.1 Step input

8.3.1.1 Driver controls

Steering-wheel input and longitudinal velocity for simulation shall be from the measured values in the physical testing.

A simulation shall be performed for each physical test defined in 7.5.1.1.

8.3.1.2 Data analysis

Response time, peak response time, and overshoot values shall be calculated for a simulation using the same method in 7.5.1.2

8.3.1.3 Data presentation

For each simulation, the time histories of steering-wheel angle, lateral acceleration, yaw velocity, and longitudinal velocity, as shown in ISO 7401:2011, Figure B.1, shall be plotted. The same curve fitting method for measured data as in 7.5.1.3 shall be applied.

The values defined in 7.5.1.3 shall be calculated using the same computation method as in measured data.

8.3.2 Sinusoidal input — One period

8.3.2.1 Driver controls

Steering-wheel input and longitudinal velocity for simulation shall be from measured values in the physical testing.

A simulation shall be performed for each physical test defined in 7.5.2.1.

8.3.2.2 Data analysis

Lateral acceleration, yaw velocity, time lags, lateral acceleration gain, yaw velocity gain for each simulation shall be calculated using the same method as in 7.5.2.2.

8.3.2.3 Data presentation

For each simulation, the time histories of lateral acceleration and yaw velocity, time lags, lateral acceleration gain, yaw velocity gain as shown in ISO 7401:2011, Figure B.2, shall be computed. The same curve fitting method for measured data as in 7.5.2.3 shall be applied.

8.3.3 Random input

8.3.3.1 Driver controls

Steering-wheel input and longitudinal velocity for simulation shall be from the measured values in the physical testing.

Duration of number of simulations shall correspond to those of physical tests specified in 7.5.3.1.

8.3.3.2 Data analysis

The same data processing such as using a multi-channel real time analyser or a computer with the appropriate software adopted in physical testing as in 7.5.3.2 shall be applied to the data extracted from simulation.

Preliminary Fourier analysis for steering-wheel angle time history (see ISO 7401:2011, 12.2.2) is not necessary for simulation.

Data processing for transfer function amplitude and phase information for lateral acceleration related to steering-wheel angle and yaw velocity related to steering-wheel angle (see ISO 7401:2011, 12.2.3) shall be performed with the same method employed in the measured data processing.

In case data has not been captured in a continuous run in physical testing, and the results of individual runs are averaged, then the same procedure shall be taken for data from simulation.

8.3.3.3 Data presentation

Time histories of variables used for data evaluation shall be plotted. If a curve is fitted to any set of measured data, the same method of curve fitting shall be applied to data from simulation.

For each pair of input and output variables, the frequency response (i.e. gain and phase-angle functions) shall be presented on a graph as shown in ISO 7401:2011, Figure B.4. The number and length of the data sequences, the averaging function, the digitizing rate and the windowing function applied to the measured data shall be applied to the data from simulation.

8.3.4 Pulse input

8.3.4.1 Driver controls

Steering-wheel input and longitudinal velocity for simulation shall be from measured values in the physical testing.

A simulation shall be performed for each physical test defined in 7.5.4.1.

8.3.4.2 Data analysis

The same data processing such as using a multi-channel real time analyser or a computer with the appropriate software adopted in physical testing as in 7.5.4.2 shall be applied to the data extracted from simulation.

Preliminary Fourier analysis for steering-wheel angle time history (see ISO 7401:2011, 13.2.2) is not necessary for simulation.

Data processing for transfer function amplitude and phase information for lateral acceleration related to steering-wheel angle and yaw velocity related to steering-wheel angle (see ISO 7401:2011, 13.2.3) shall be performed with the same method employed in measured data processing. The transfer functions of at least three test runs shall be averaged.

8.3.4.3 Data presentation

Time histories of variables used for data evaluation shall be plotted. If a curve is fitted to any set of measured data, the same method of curve fitting shall be applied to data from simulation.

For each pair of input and output variables, the frequency response (i.e. gain and phase-angle functions) shall be presented on a graph as shown in ISO 7401:2011, Figure B.4. The number and length of the data sequences, the averaging function, the digitizing rate and the windowing function applied to measured data shall be applied to simulated data.

8.3.5 Continuous sinusoidal input

8.3.5.1 Driver controls

Steering-wheel input and longitudinal velocity for simulation shall be from measured values in the physical testing.

Number and duration of simulations shall be corresponding to those of physical testing as specified in 7.5.5.1.

8.3.5.2 Data analysis

Amplitude of steering wheel angle, lateral acceleration gain and yaw velocity gain as specified in 7.5.5.2 shall be calculated. All amplitudes shall be taken at the same time interval of physical testing where the vehicle is in a periodic steady-state condition.

Lateral acceleration gain, yaw velocity gain, and phase angle shall be calculated as specified in ISO 7401:2011, 14.2.2 to 14.2.5.

Phase angles between the steering-wheel angle and the lateral acceleration and yaw velocity shall be determined from the time histories after the first period, when the vehicle is in a periodic steady-state condition.

8.3.5.3 Data presentation

Time histories of variables used for data evaluation shall be plotted. If a curve is fitted to any set of measured data, the same method of curve fitting shall be applied to data from simulation.

For each pair of input and output variables, the frequency response (i.e. gain and phase-angle functions) shall be presented on a graph as shown in ISO 7401:2011, Figure B.4. The number and length of the data sequences, the averaging function, the digitizing rate and the windowing function applied to measured data shall be applied to simulated data.

9 Comparison between simulation and physical test results

9.1 Step input

The following characteristic values in Table 1 obtained from measurements and simulation shall be compared. If all the percent errors in the shaded boxes in Table 1 are within the specified tolerance, the simulation tool is valid.

In Table 1, tolerances of percent errors are uniformly given as 15 %, which is the minimum requirement for validation. Depending on the purpose of applications, different percent error values can be adopted by agreement between parties involved. If this is the case, the adopted values shall be reported.

Response time, peak response time, steady-state gain and overshoot values for roll angle, roll rate and sideslip angle (variables in the shaded boxes at the lower part of the first column) that are not performance metrics from ISO 7401, may be adopted for optional validation if agreed between parties involved.

Additionally, time histories of lateral acceleration, yaw velocity, roll angle, roll rate and sideslip angle from measured and simulated data should be compared for validation of settling behaviour to steady-state condition.

Table 1 — Step input — Response data validation

Longitudinal speed, v_x = 100,0 km/h (or other value__________km/h)
Lateral acceleration, a_Y = 4,0 m/s² (or other value__________m/s²)

Parameter	Symbol	Unit	Tolerance of percent error [%]	Values & percent error	Left turn			Right turn		
					1st	2nd	3rd	1st	2nd	3rd
Steady-state yaw velocity response gain	$\left(\frac{\dot{\psi}}{\delta_H}\right)_{ss}$	s^{-1}	15,0	a a)						
				b b)						
				c c)						
Lateral acceleration response time	T_{a_Y}	s	15,0	a						
				b						
				c						
Yaw velocity response time	$T_{\dot{\psi}}$	s	15,0	a						
				b						
				c						
Lateral acceleration peak response time d)	$T_{a_{Y\,max}}$	s	15,0	a						
				b						
				c						
Yaw velocity peak response time d)	$T_{\dot{\psi}_{max}}$	s	15,0	a						
				b						
				c						

a) Measured value.

b) Simulated value.

c) Percent error c=ABS（(b-a)/b）x100.

d) For the vehicle that does not shows overshoot response, these metrics can be skipped for validation.

e) Optional validation metrics.

Table 1 *(continued)*

Parameter	Symbol	Unit	Tolerance of percent error [%]	Values & percent error	Left turn			Right turn		
					1st	2nd	3rd	1st	2nd	3rd
Overshoot value of lateral acceleration d)	U_{a_Y}	—	15,0	a						
				b						
				c						
Overshoot value of yaw velocity d)	$U_{\dot{\psi}}$	—	15,0	a						
				b						
				0						
Roll angle response time e)	T_{ϕ}	s	15,0	a						
				b						
				c						
peak response time e)	$T_{\phi_{max}}$	s	15,0	a						
				b						
				c						
Steady state roll angel gain e)	$\left(\dfrac{\phi}{\delta_H}\right)_{ss}$	—	15,0	a						
				b						
				c						
Overshoot value of roll rate d),e)	$U_{\dot{\phi}}$	—	15,0	a						
				b						
				c						
Roll rate response time e)	$T_{\dot{\phi}}$	s	15,0	a						
				b						
				c						
Roll rate peak response time d),e)	$T_{\dot{\phi}_{max}}$	s	15,0	a						
				b						
				c						
Steady state roll rate gain e)	$\left(\dfrac{\dot{\phi}}{\delta_H}\right)_{ss}$	s^{-1}	15,0	a						
				b						
				c						
Overshoot value of roll rate d),e)	$U_{\dot{\phi}}$	—	15,0	a						
				b						
				c						
Sideslip angle response time e)	T_{2}	s	15,0	a						
				b						
				c						

a) Measured value.

b) Simulated value.

c) Percent error c=ABS〔(b-a)/b〕x100.

d) For the vehicle that does not shows overshoot response, these metrics can be skipped for validation.

e) Optional validation metrics.

Table 1 *(continued)*

Parameter	Symbol	Unit	Toler-ance of percent error [%]	Values & percent error	Left turn			Right turn		
					1st	2nd	3rd	1st	2nd	3rd
Sideslip angle peak response time [d),e)]	$T_{\beta max}$	s	15,0	a						
				b						
				c						
Steady state sideslip angle gain [e)]	$\left(\frac{\beta}{\delta_H}\right)_{ss}$	—	15,0	a						
				b						
				c						
Overshoot value of Side-slip angle [d),e)]	U_β	—	15,0	a						
				b						
				c						

a) Measured value.

b) Simulated value.

c) Percent error c=ABS〔(b-a)/b〕x100.

d) For the vehicle that does not shows overshoot response, these metrics can be skipped for validation.

e) Optional validation metrics.

9.2 Sinusoidal input — One period

The following characteristic values obtained from measurements and simulation shall be compared. If all percent errors in the shaded boxes in Table 1 are within the specified tolerance, the simulation tool is valid.

In Table 1, tolerances of percent errors are uniformly given as 15 %, which is the minimum requirement for validation. Depending on the purpose of applications, different percent error values can be adopted by agreement between parties involved. If this is the case, the adopted values shall be reported.

Time lag and gain for roll angle, roll rate and sideslip angle (variables in the shaded cell at the first column) that are not performance metrics from ISO 7401 may be adopted for optional validation if agreed between parties involved.

Additionally, time histories of lateral acceleration and yaw velocity, and optionally roll angle, roll rate sideslip angle, from measured and simulated data should be compared for validation.

Table 2 — Sinusoidal input (one period) — Response data validation

Longitudinal speed, v_x = 100,0 km/h (or other value____________________Km/h)

Lateral acceleration, a_Y = 4,0 m/s^2 (or other value____________________m/s^2)

Parameter	Symbol	Unit	Tolerance of percent error [%]	Values & percent error	Left turn			Right turn		
					1st	2nd	3rd	1st	2nd	3rd
Lateral acceleration time lag Peak 1	$T_{(\delta_H \text{-} a_Y)_1}$	ms	15,0	a[a]						
				b[b]						
				c[c]						
Lateral acceleration time lag Peak 2	$T_{(\delta_H \text{-} a_Y)_2}$	ms	15,0	a						
				b						
				c						
Yaw velocity time lag Peak 1	$T_{(\delta_H \text{-} \dot{\psi})_1}$	ms	15,0	a						
				b						
				c						
Yaw velocity time lag Peak 2	$T_{(\delta_H \text{-} \dot{\psi})_2}$	ms	15,0	a						
				b						
				c						
Lateral acceleration gain	$\frac{a_Y}{\delta_H}$	(m/s^2)/deg	15,0	a						
				b						
				c						
Yaw velocity gain	$\frac{\dot{\psi}}{\delta_H}$	s^{-1}	15,0	a						
				b						
				c						
Roll angle time lag Peak 1[d]	$T_{(\delta_H - \phi)_1}$	ms	15,0	a						
				b						
				c						
Roll angle time lag Peak 2[d]	$T_{(\delta_H - \phi)_2}$	ms	15,0	a						
				b						
				c						
Roll angle gain[d]	$\frac{\phi}{\delta_H}$	—	15,0	a						
				b						
				c						
Roll rate time lag Peak 1[d]	$T_{(\delta_H - \dot{\phi})_1}$	ms	15,0	a						
				b						
				c						
Roll rate time lag Peak 2[d]	$T_{(\delta_H - \dot{\phi})_2}$	ms	15,0	a						
				b						
				c						

a) Measured value.

b) Simulated value.

c) Percent error c=ABS ((b-a)/b) x100.

d) Optional validation metrics.

Table 2 *(continued)*

Parameter	Symbol	Unit	Tolerance of percent error [%]	Values & percent error	Left turn			Right turn		
					1st	2nd	3rd	1st	2nd	3rd
Roll rate gain d)	$\frac{\dot{\phi}}{\delta_H}$	s^{-1}	15,0	a						
				b						
				c						
Sideslip angle time lag Peak 1 d)	$T_{(\delta_H\text{-}^2)_1}$	ms	15,0	a						
				b						
				c						
Sideslip angle time lag Peak 2 d)	$T_{(\delta_H\text{-}^2)_2}$	ms	15,0	a						
				b						
				c						
Sideslip angle Gain	$\frac{\beta}{\delta_H}$	—	15,0	a						
				b						
				c						

a) Measured value.

b) Simulated value.

c) Percent error c=ABS（(b-a)/b）x100.

d) Optional validation metrics.

9.3 Random input, pulse, and continuous sinusoidal input

9.3.1 General

The amplitude and phase of the frequency response (i.e. gain and phase-angle functions) of the measured lateral acceleration and yaw velocity with respect to steering-wheel angle shall be presented on a graph as shown in Figure 1 and 2. The frequency range shall be at least up to 2,0 Hz with resolution of 0,1Hz.

Frequency response from simulation are considered to be fully repeatable and reproducible, and are used to calculate upper and lower boundaries for the purpose of determining whether the simulation is valid when compared to data points from physical testing.

9.3.2 Calculation of boundary point

Given a set of frequency values from simulation associated with the X-axis and a set of values of another variable from simulation associated with the Y-axis (phase angel or gain), the *X* and *Y* coordinates for the top boundary as shown in Figures 1 and 2 are given in Formula (1) to Formula (5):

$$X_T = X - \Delta Y\, \varepsilon_X^2 / D \quad (1)$$

$$Y_T = Y + \Delta X\, \varepsilon_Y^2 / D \quad (2)$$

The X and Y coordinates for the bottom boundary are:

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

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

where $D = [(\Delta X\, \varepsilon_Y)^2 + (\Delta Y\, \varepsilon_X)^2]^{1/2}$ (5)

and ΔX is the difference between the X-axis variable for the current value and preceding value (with original units such as Hz), ΔY is the difference between the Y-axis variable (phase angel or gain) for the current value and preceding value, ε_X is the tolerance for the frequency, and ε_Y is the tolerance for the Y- axis variable.

NOTE See ISO 19364:2016, Annex A for the derivation of Formula (1) to (5).

9.3.3 Tolerance for frequency function

Tolerances ε_x and ε_y for each frequency functions are calculated using an offset and gain with Formulae (6) and (7):

$$\varepsilon_X = [X_{offset}] + [X_{gain}] \times |X| \quad (6)$$

$$\varepsilon_Y = [Y_{offset}] + [Y_{gain}] \times |Y| \quad (7)$$

Offset and gain values for frequency functions of yaw rate and lateral acceleration are listed in Table 3.

Depending on the purpose of applications, different offset and gain values can be used by agreement between parties involved. If this is the case, the adopted values shall be provided in the report.

Frequency function for roll rate, even though that is not required in ISO 7401, may be subject to optional validation if agreed between parties involved. Its nominal offset and gain values are given in Table 3 in the shaded cells to demonstrate its optional status.

Another optional performance metric for validation that can be adopted by agreement is resonance frequency percent error between simulation and measurement, which can be given as Formula (8):

$$ABS[(f_{r,m} - f_{r,s})/f_{r,s}] \times 100 \quad (8)$$

where $f_{r,m}$ and $f_{r,s}$ represent resonant frequency from measurement and simulation, respectively. The nominal value of resonance frequency percent error is 15,0 %, which can be differently set depending on the purpose of application by agreement between parties involved.

Table 3 — Offsets and gains used to define tolerances ε_X and ε_Y for frequency domain tests

Variable on Y axis	X offset	X gain	Y offset	Y gain
Yaw velocity gain[a)] [(deg/s)/deg]	0,15 [Hz]	0,15	0,05[(deg/s)/deg]	0,15
Yaw velocity phase angle [deg]	0,15 [Hz]	0,15	10,0 [deg]	0,15
Lateral acceleration gain[b)] [(m/s^2)/deg]	0,15 [Hz]	0,15	0,05[(m/s^2)/deg]	0,15
Lateral acceleration phase angle [deg]	0,15 [Hz]	0,15	10,0 [deg]	0,15

a) Yaw rate/steering-wheel angle.

b) Lateral acceleration/steering-wheel angle.

c) Roll rate/steering-wheel angle.

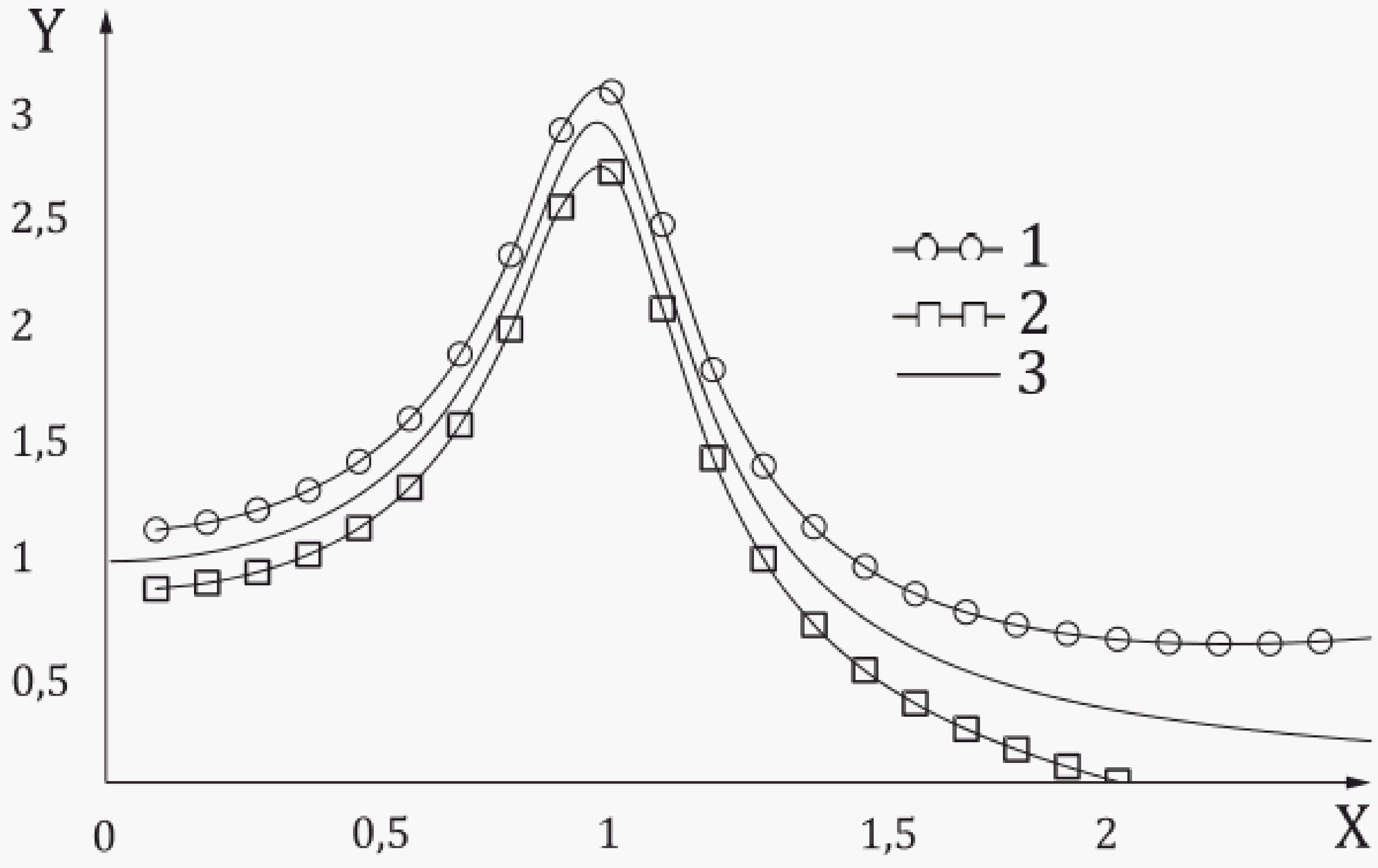
d) Optional validation metrics.

Table 3 *(continued)*

Variable on Y axis	X offset	X gain	Y offset	Y gain
Roll rate gain[c)] [(deg/s)/deg]	0,15 [Hz]	0,15	0,015[(deg/s)/deg]	0,15
Roll rate phase angle[d)] [deg]	0,15 [Hz]	0,15	10,0 [deg]	0,15
a) Yaw rate/steering-wheel angle.				
b) Lateral acceleration/steering-wheel angle.				
c) Roll rate/steering-wheel angle.				
d) Optional validation metrics.				

9.3.4 Validation criteria

If the test results all lie within the boundaries, then the simulation tool is considered valid for determining transient behaviour in frequency domain.



Key

X frequency, in Hz

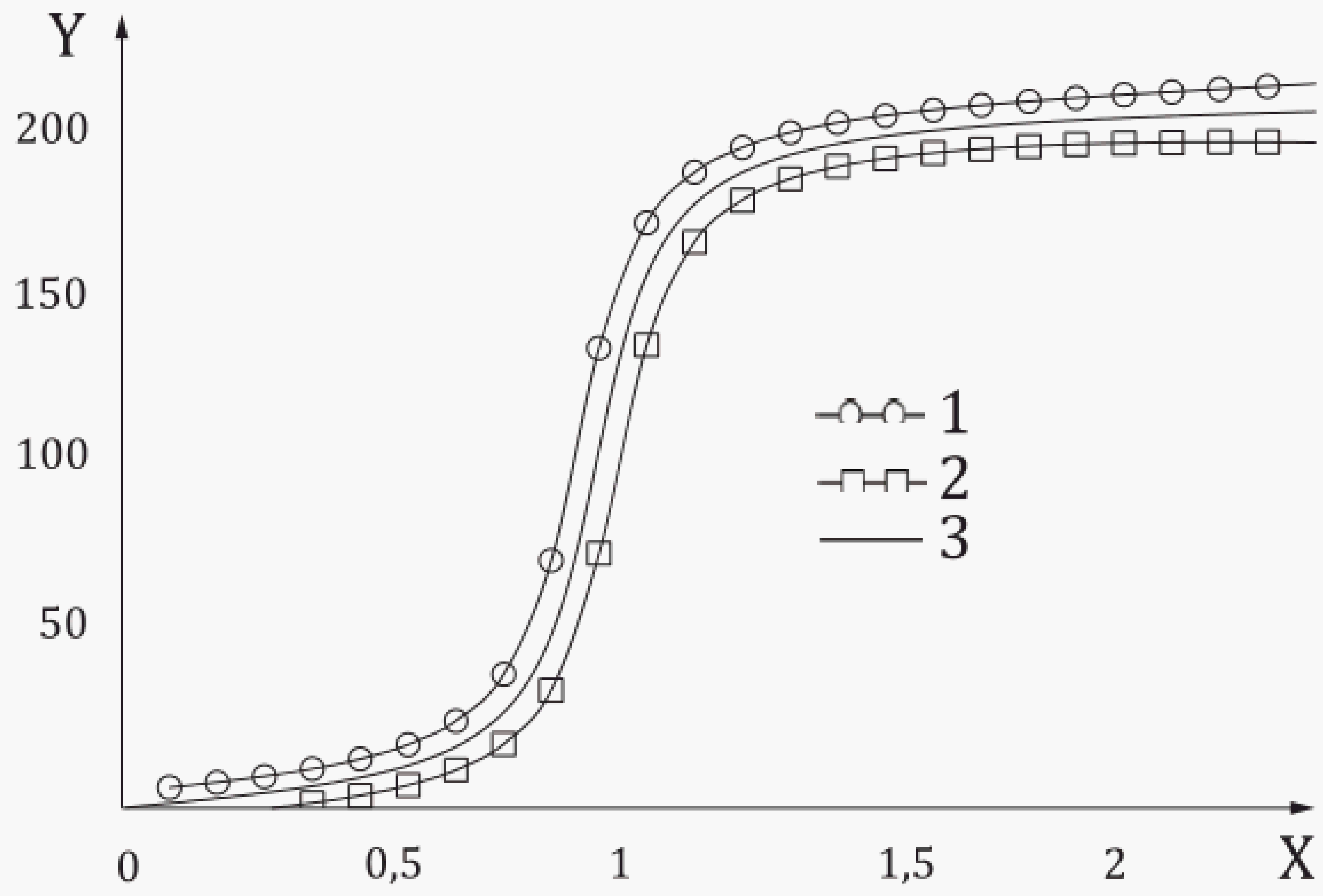
Y gain

1 top boundary points

2 bottom boundary points

3 simulated curve

Figure 1 — Frequency response function (gain)



Key

X frequency, in Hz

Y phase, in deg

1 top boundary points

2 bottom boundary points

3 simulated curve

Figure 2 — Frequency response function (phase)

10 Documentation

If driver can select a control mode for any active intervention system, the selected mode shall be reported.

The simulation should be documented to the extent needed to reproduce the simulated tests. This should include names of software tools, including version numbers, and internal model names. A list of files used to run the simulation shall be provided, and copies of the files shall be archived.

Bibliography

[1] ISO 19364:2016, *Passenger cars — Vehicle dynamic simulation and validation — Steady-state circular driving behaviour*

[2] ISO 19365, *Passenger cars — Validation of vehicle dynamic simulation — Sine with dwell stability control testing*

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