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Heavy commercial vehicles and buses – Vehicle dynamics simulation and validation – Closing-curve test

Véhicules utilitaires lourds et autobus – Simulation et validation dynamique des véhicules – Essai en courbe se fermant

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Contents

Foreword

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ISO 21233 was prepared by Technical Committee ISO/TC 22, *Road vehicles*, Subcommittee SC 33, *Vehicle dynamics and chassis components, WG6 Vehicle dynamics of heavy commercial vehicles and buses.*

Introduction

The main purpose of this International Standard 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 must necessarily involve 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 – Closing-curve test

1 Scope

This International Standard specifies a method for comparing simulation results from a mathematical vehicle model to measured test data for an existing vehicle according to closing-curve tests as specified in ISO 11026:2011. The comparison is made for the purpose of validating the simulation tool for this type of test. The intention of the validation is to demonstrate that the vehicle dynamics simulation, combined with an integrated electronic stability control (ESC) system, can predict the vehicle behaviour during the closing curve test including interventions of the ESC system. The simulation method can be either hardware-in-the-loop (with the original electronic control unit (ECU) on a HiL test stand) or software-in-the-loop, based on a code generated from the same source as for the ECU in the real vehicle. The standard 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, in whole or in part, are normatively referenced in this document and are indispensable for its application. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

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

ISO 8855:2011, *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 commercial vehicles and buses*

ISO 11026:2011, *Heavy commercial vehicles and buses – Test method for roll stability — Closing-curve test*

ISO 19585:2019, *Heavy commercial vehicles and buses – Vehicle dynamics simulation and validation – Steady-state circular driving behaviour*

3 Terms and definitions

For the purpose of this standard, the terms and definitions given in ISO 3833, ISO 8855:2011, ISO 15037-2:2002, ISO 11026:2011, ISO 19585:2019 and the following apply.

3.1 Software-in-the-Loop (SiL)

Method of integrating the electronic stability system into the vehicle dynamics simulation by a software code generated from the same source as for the vehicle ECU

3.2 Hardware-in-the-Loop (HiL)

Method of integrating the electronic stability system into the vehicle dynamics simulation by integrating both the vehicle simulation model and the hardware of the electronic control unit into a real time ECU test stand

3.3 ESC intervention time

Point in time during a single test where the first ESC (drivetrain or brake) intervention occurs

3.4 Intervention steering wheel angle

Steering wheel angle at the *ESC intervention time*

3.5 Intervention yaw velocity

Yaw velocity at the *ESC intervention time*

3.6 Intervention lateral acceleration

Lateral acceleration at the *ESC intervention time*

3.7 Maximum initial velocity

Maximum constant initial velocity for the reference path, when no wheel lift-off occurs during the test and at which the vehicle can still be kept on the desired path (for a pre-defined steering wheel input)

4 Principle

The test methods defined in ISO 11026:2011 are used to determine the rollover stability of heavy commercial vehicles and buses as defined in ISO 3833. The test methods are designed for vehicles equipped with an electronic stability control (ESC).

Within this International Standard, the purpose of the test is to demonstrate that a vehicle simulation tool can predict the vehicle behaviour within specified tolerances. The vehicle simulation tool is used to simulate a specific existing vehicle which is also tested physically, using one of the closing-curve test methods specified in ISO 11026:2011 for both test and simulation. Measurement results are used to define reference curves and characteristic values, and the respective simulation results are compared to analyse the deviation between physical testing and simulation.

Prior to the validation of the vehicle simulation model for the closing-curve test, a validation of the model for steady-state cornering according to ISO 19585 shall be conducted. In addition to this basic validation, the validation done according to this International Standard serves to demonstrate that the simulation model correctly predicts wheel lift-off during the Closing Curve test and that ESC interventions are represented correctly by the simulation 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 8855:2011). For the purpose of this International Standard, the reference point shall be the centre of gravity of the first vehicle unit. This provision overrides the similar provision of ISO 15037-2:2002. Measurement requirements shall be taken from ISO 11026:2011 and ISO 15037-2:2002. The variables that shall be determined for compliance with this International Standard are:

- longitudinal velocity, v_x;
- steering-wheel angle, δ_H;
- lateral acceleration, a_y;
- yaw velocity, $\dot{\psi}$;
- intervention flags (ESC output values) for both drivetrain and brake control;
- desired engine torque limit (ESC output values);
- desired brake torque (ESC output values);
- Wheel speed sensor signals (as an indication for lift-off of the inner wheels).

It is recommended that the following variables are also determined:

- side slip angle of first vehicle unit;
- roll angle of first vehicle unit;
- steering wheel angle velocity;
- roll angle(s) of the towed vehicle unit(s) at relevant points;
- articulation angle(s) between the vehicle units;
- type of ESC intervention (yaw control or roll stability control);
- vehicle path of the reference point of the first vehicle unit

NOTE For measuring lateral acceleration, yaw velocity and steering wheel angle, it is sufficient to use the ESC sensor data from the vehicle bus system.

6 Simulation model parameters and requirements

6.1 General

The simulation tool 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 International Standard, the mathematical model is used to simulate the closing-curve test method described in section 7.2 and provide calculated values of the variables of interest from section 5.

Prior to the validation of the vehicle simulation model for the closing-curve test, a validation of the model for steady-state cornering according to ISO 19585 shall be conducted. Correspondingly, all definitions about simulation model parameters and requirements included in ISO 19585, clause 6, shall apply, together with the following additional specifications for the closing-curve test and the interventions of the electronic stability control.

6.2 Basic vehicle parameters

For the basic vehicle parameters of the simulation model, the same definition as described in ISO 19585, clause 6.2, shall apply.

6.3 Estimated vehicle parameters

For the representation of the estimated vehicle parameters within the simulation model, the same definition as described in ISO 19585, clause 6.3, shall apply, together with the following additions.

6.3.1 Principal moments of inertia

The initial values of the principal moments of inertia shall be derived from measurements or design data and should not be altered more than +/- 25% during the validation process.

6.3.2 Tyre force characteristics

Additional to the definitions specified for the lateral tyre force characteristics in ISO 19585, clause 6.2, the tyre model should represent the transient tyre force behaviour.

Because of the braking interventions of the electronic stability control, the tyre model of the simulation shall include the longitudinal tyre force behaviour and a representation of the combined slip behaviour. It is recommended that (on a dry and even road surface) the deviation of the characteristic curves of the longitudinal tyre force versus tyre slip used in the tyre model and the curves of the tyre measurement should not exceed +/- 20% for a tyre slip below 20%. 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.

6.3.3 Damper characteristics

The initial values of the characteristics of the axle dampers shall be derived from measurements or design data and should not be altered more than +/- 10% during the validation process. As during the closing-curve test no high damper velocities will be reached, linear coefficients may be sufficient for the validation. If the simulation model includes a separate cabin mass, the same definitions apply for the cabin dampers.

6.4 Electronic stability control

The electronic stability control used in the simulation model shall have the same release number as the control unit used in the test vehicle. The ESC parameters for the simulation and for the test vehicle shall be the same and shall be documented.

When using the software-in-the-loop (SiL) method to combine the ESC functionality with the vehicle simulation model, a software code of the electronic stability control or the complete electronic brake system delivered by the system supplier is integrated into the vehicle simulation model. This code should also contain a representation of the anti-lock braking system (ABS). The data transferred from the vehicle model to the ESC (and ABS) system and vice versa should be consistent and agreed upon between the system supplier and the user of the simulation model. Typically, the data submitted from the vehicle simulation model to the system code are the same as the sensor data transferred in the real vehicle, e.g. steering wheel angle, wheel sensor signals, yaw velocity and lateral acceleration. It is therefore recommended that the simulation model contains a sensor for yaw velocity and lateral acceleration which is placed at the same geometric location as in the real vehicle. The minimum output given from the system code to the vehicle simulation model within the simulation loop are the flags of the drivetrain and braking interventions of the system and the desired drivetrain torque and brake torque. It is recommended that additional values to monitor the correct functionality of the system code in the simulation loop are given from the system code to the vehicle simulation model.

When using the hardware-in-the-loop (HiL) method to combine the system with the simulation model, both the vehicle simulation model and the hardware of the electronic control unit (ECU) are integrated into a HiL test bench. In this case, additional exchange between the ECU and the vehicle simulation model will be necessary to have a correct functionality of the control unit on the test bench. It should be documented that the ECU was in an error-free status when conducting the test on the HiL test bench.

When conducting the validation for a vehicle combination, where the trailer is also equipped with an electronic stability system, it is necessary that the simulation model contains also a representation of the ESC of the trailer. This can be done either by implementing also a SiL code or, for HiL testing, an electronic control unit of the trailer stability system, or by a simplified representation of the trailer stability control on the basis of information given from the supplier of the trailer stability control.

NOTE As the electronic braking system typically contains learning algorithms to identify vehicle parameters, e.g. the vehicle mass, it may be necessary to conduct other driving manoeuvers with the vehicle simulation model prior to the closing-curve test, such as accelerating and braking straight ahead, and to monitor the “learnt” values such as vehicle mass as output values of the ESC.

6.5 Braking system

For representing correctly the braking interventions of the electronic stability control, the simulation shall include a model of the braking system which contains the dynamic response of the vehicle brakes to the brake torque desired by the electronic stability system and a representation of the braking forces at the wheels induced by the given brake torque (e.g., including the braking force distribution between the vehicle axles). For vehicle combinations, this includes the braking system of the trailer(s).

NOTE 1 When using the SiL method, the representation of the braking system may be either part of the vehicle simulation model or part of the software code delivered by the system supplier. When using the HiL method, either the vehicle simulation model may contain a model of the braking system, or the braking system may be included physically in the test stand.

NOTE 2 For proving correct functionality of the braking system (and the ABS) within the simulation loop, it is recommended to compare results of field tests and simulations of braking straight ahead with maximum brake torque, according to ISO 16552:2014.

6.6 Additional model requirements

For additional model requirements, the definitions described in ISO 19585, clause 6.2, shall apply.

7 Field tests

7.1 General

An existing vehicle of interest shall be tested using one of the test methods specified in ISO 11026:2011. Both the physical tests and the simulations shall be run steering clockwise and steering counter-clockwise, with ESC "on" and ESC "off". For each steering direction and each variation of initial vehicle velocity and path, at least 3 individual valid test runs shall be conducted; the criteria for a valid test run are given in ISO 11026. For the loading conditions, the definitions given in ISO 11026 apply.

The variables measured in the field test may need correction in terms of sensor location, orientation, data processing (filtering, etc.) to be comparable to the corresponding simulation signals.

7.2 Test Method

For the purpose of validation, it is recommended to use the reference path defined in ISO 11026 (which gives a jerk of 2 m/s^3 for an initial vehicle velocity of 60 km/h). Other paths specified in ISO 11026 may be used additionally and/or alternatively. As specified in ISO 11026, the deviation of the reference point of the vehicle from the intended path shall not exceed ±0,5 m. Tests with different initial vehicle velocities on the same path shall be conducted, starting with an initial velocity where no ESC intervention occurs, increasing the initial vehicle velocity in steps not more than 5 km/h, and finishing with an initial velocity where the recorded wheel speed sensor signals indicate a liftoff of an inner wheel or where severe over- or understeer conditions are observed, so that the vehicle cannot be kept on the defined path. This longitudinal velocity shall be reported as maximum initial velocity. Additionally, if wheel lift-off occurs during the tests, the lateral acceleration at which the first liftoff of an inner wheel occurs shall be reported, and the order of wheel lift-off (e.g. first lift-off at the inner rear driven axle) shall be reported.

NOTE As ESC systems usually contain intervention thresholds which are dependent on vehicle velocity and steering wheel angle velocity, the intervention lateral acceleration may be different for different values of jerk and should then be reported together with the steering wheel velocity.

7.3 Evaluation of test results

The curves of the variables listed in clause 5 versus time shall be plotted for each valid test run. For the purpose of comparison with the simulation results, a representative curve shall be chosen from each valid series of test runs.

The following characteristic values shall be evaluated for each valid test run:

- Intervention steering wheel angle
- Intervention lateral acceleration
- First peak value (first maximum value) of the lateral acceleration
- Intervention yaw velocity
- First peak value (first maximum value) of the yaw velocity
- Point in time, steering wheel angle and lateral acceleration for the first inner wheel lift-off, order of inner wheel lift-off

Additionally, the maximum initial velocity shall be documented for each series of valid test runs.

8 Simulation

8.1 General

The simulation shall be conducted with the same test method as used for physical testing. From the simulation, the same characteristic curves and values shall be determined as described in clause 7.3 for physical testing.

The simulation of the closing-curve test should be conducted as an open-loop test, with the steering wheel angle measured during the chosen representative test results serving as input to the steering system of the simulation model. Alternatively, a ramp steer input with a linear increase of the steering wheel angle may be used, which results in the same value of jerk (2 m/s^3 (+/- 5%) for the recommended path from ISO 11026:2011) as used in the field test. The initial vehicle velocity for the simulation of the Closing Curve manoeuvre shall be set to the same value as measured in the real test run, with a maximum deviation of +/- 2 km/h.

NOTE Small deviations in initial vehicle velocity can lead to significantly different test results. Therefore, also the measured initial longitudinal vehicle velocity may be used as input for the initial longitudinal velocity of the simulation model.

8.2 Data recording

The output of the simulation model shall have at least the same sampling rate as the recording of the field 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 simulation tool
- Name and version number of the tyre model
- Name and version number of the ESC stability control
- ESC parameter sheet
- Internal name of vehicle model
- List and contents of input files used

9 Comparison of simulation and field tests

9.1 General

For comparing curves of the simulated and measured vehicle behaviour, at least one field test result shall be chosen, during which a braking system intervention of the electronic stability control was recorded, either by braking all wheels of the first vehicle unit (intervention of the rollover stability control) or by braking individual wheels of the first vehicle unit (intervention of the yaw stability control). It is recommended to compare additionally curves for other initial vehicle velocities. For the complete test series (with ESC “ON” and ESC “OFF”), the maximum entrance speed for the test series in the simulation and in the field test shall be reported.

9.2 Dynamic vehicle behaviour without ESC

9.2.1 Wheel lift-off

The order of inner wheel lift-off observed in the simulation model should be the same as reported from the field test. The lateral acceleration at which the first wheel lift-off occurs in simulation should be within the tolerance specified in the table in Annex A.

9.2.2 Comparison of yaw velocity and lateral acceleration

For both methods of steering input (measured steering wheel angle or ramp steer input), the steering wheel angle shall be used for time synchronization between the simulation results and the field test results. The graphs of yaw velocity and lateral acceleration versus steering wheel angle of the tests conducted with the ESC switched off serve as a basis for comparing the dynamic vehicle behaviour without the stability control of the simulation model with the results from the field tests, see Figures 1 and 2. For both driving directions and for "ESC OFF", the deviation of the characteristic values gained from simulation and from measurement should not exceed the values specified in Annex A, Table A.1.

Alternatively, curves of steering wheel angle, yaw velocity and lateral acceleration versus time may be used to compare the results of the field tests and the simulation, see Figure 3.

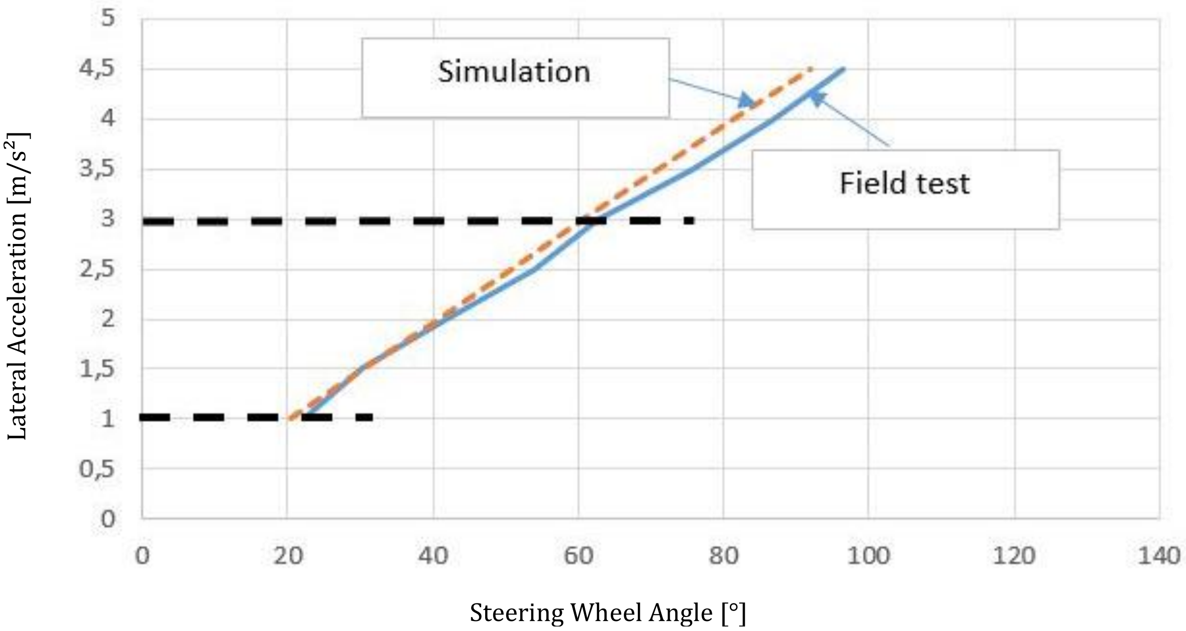

Figure 1: Lateral acceleration versus steering wheel angle, "ESC OFF", Example for comparison of simulation and measurement

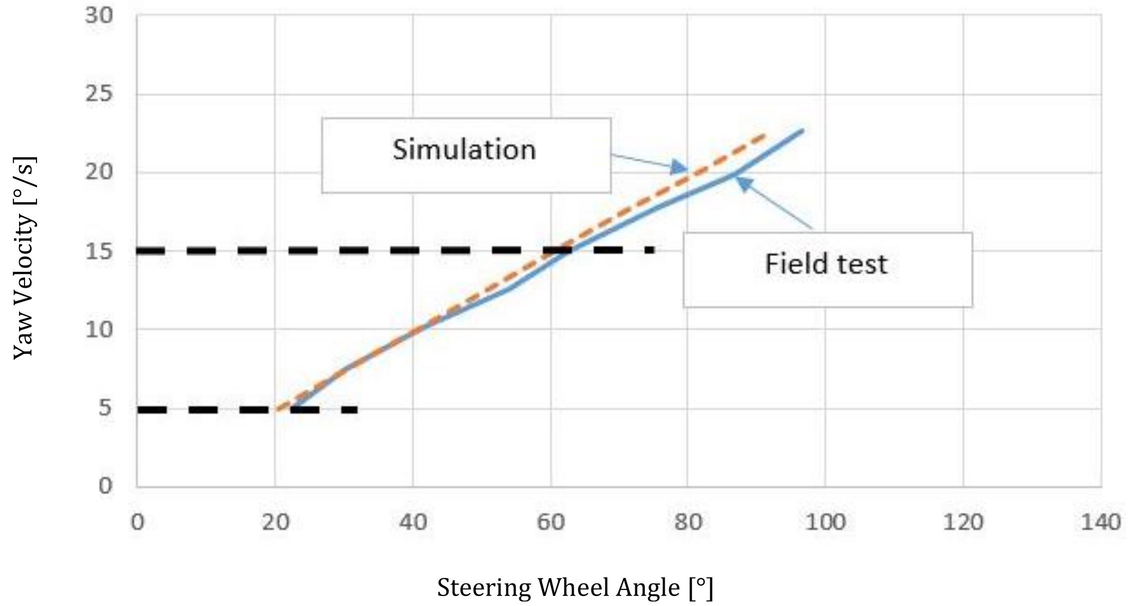

Figure 2: Yaw velocity versus steering wheel angle, "ESC OFF",
Example for comparison of simulation and measurement

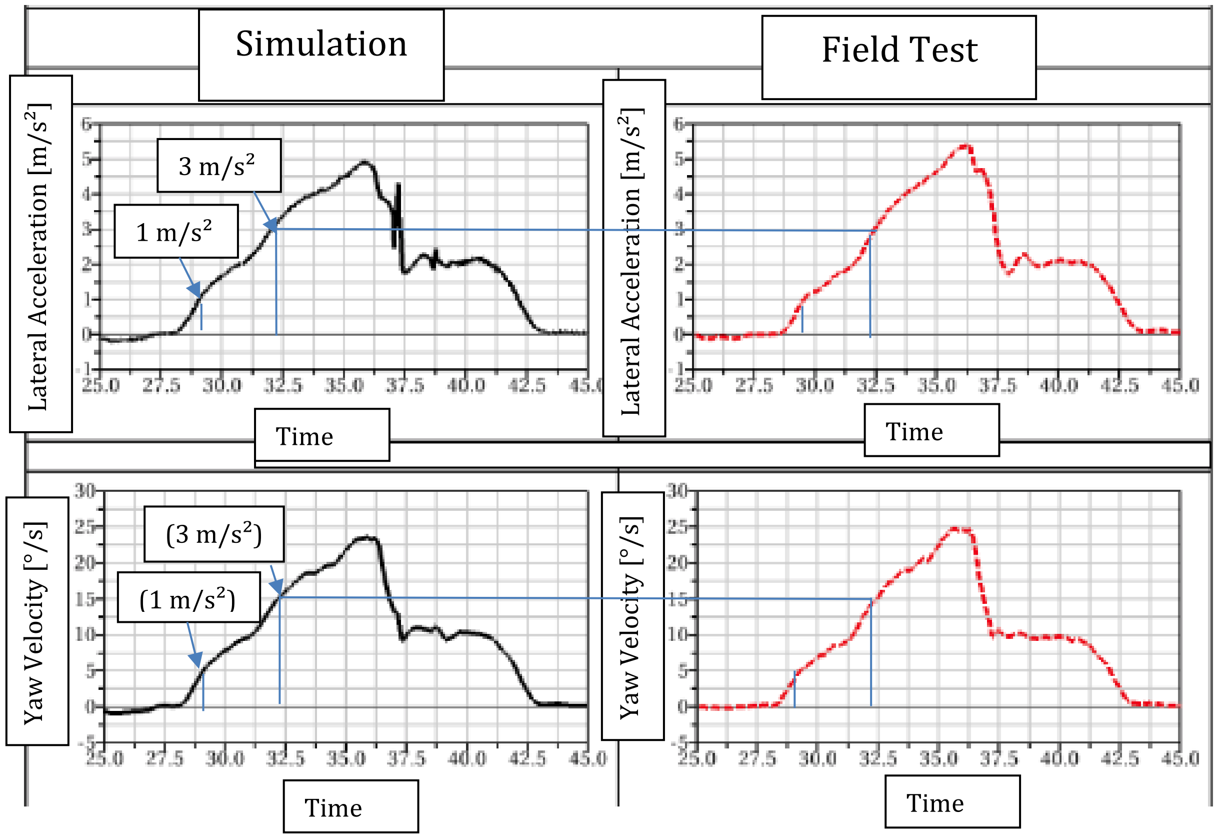

Figure 3: Yaw velocity and lateral acceleration versus time (simulation with measured steer input),
Example for comparison of simulation (left) and measurement (right), "ESC OFF"

The curves of measurement and simulation are compared in the region between the steering wheel angle, for which the measured lateral acceleration reaches 1 m/s^2, until the steering wheel angle, for which the measured lateral acceleration reaches 3 m/s^2, see Figure 3. Between these points, the mean relative deviation between the measured and the simulated curve of both lateral acceleration and yaw velocity shall be reported and should not exceed the values given in Annex A, Table A.1. The mean relative deviations of lateral acceleration and yaw velocity, s_{ay} and $s_{\dot{\psi}}$, shall be derived by using at least 10 (measured or simulated) points between the boundaries, computing their mean value and the standard deviation from:

$$s_{ay} = \sqrt{\frac{1}{n}\sum_{i=1,n}(a_{y,s,i} - a_{y,m,i})^2}$$

with $a_{y,s,i}$ and $a_{y,m,i}$ being the lateral acceleration values from simulation and measurement for the same chosen value of steering wheel angle and

$$s_{\dot{\psi}} = \sqrt{\frac{1}{n}\sum_{i=1,n}(\dot{\psi}_{s,i} - \dot{\psi}_{m,i})^2}$$

with $\dot{\psi}_{s,i}$ and $\dot{\psi}_{m,i}$ being the yaw velocity values from simulation and measurement for the same chosen value of steering wheel angle.

9.3 Dynamic vehicle behaviour with ESC

9.3.1 General

For the test series with the ESC switched on, characteristic values of yaw velocity and lateral acceleration or steering wheel angle gained from the measurement and the simulation are compared. As for the vehicle behaviour without ESC, the steering wheel angle shall be used for time synchronization between measurement and simulation.

9.3.1 ESC intervention

The graphs of the intervention flags and desired brake pressures of the electronic stability control versus time shall serve as a basis for comparing the interventions of the ESC system implemented in the simulation model with the system interventions during the chosen representative field test (for synchronization of the measured and simulated time signals see clause 9.2), see Figure 4. For proving good correlation, the following criteria should be fulfilled, see Annex A, Table A.1:

- The simulation should show the same type of intervention (either rollover stability control or yaw stability control) as the field test and shall also show the ESC drivetrain interventions.
- The lateral acceleration and the yaw velocity at which the first ESC intervention occurs in the simulation model should be within +/- 10% of the respective values during the field test.
- The maximum desired brake torque of the first ESC braking intervention in the simulation should be within +/- 25% of the respective values during the field test.

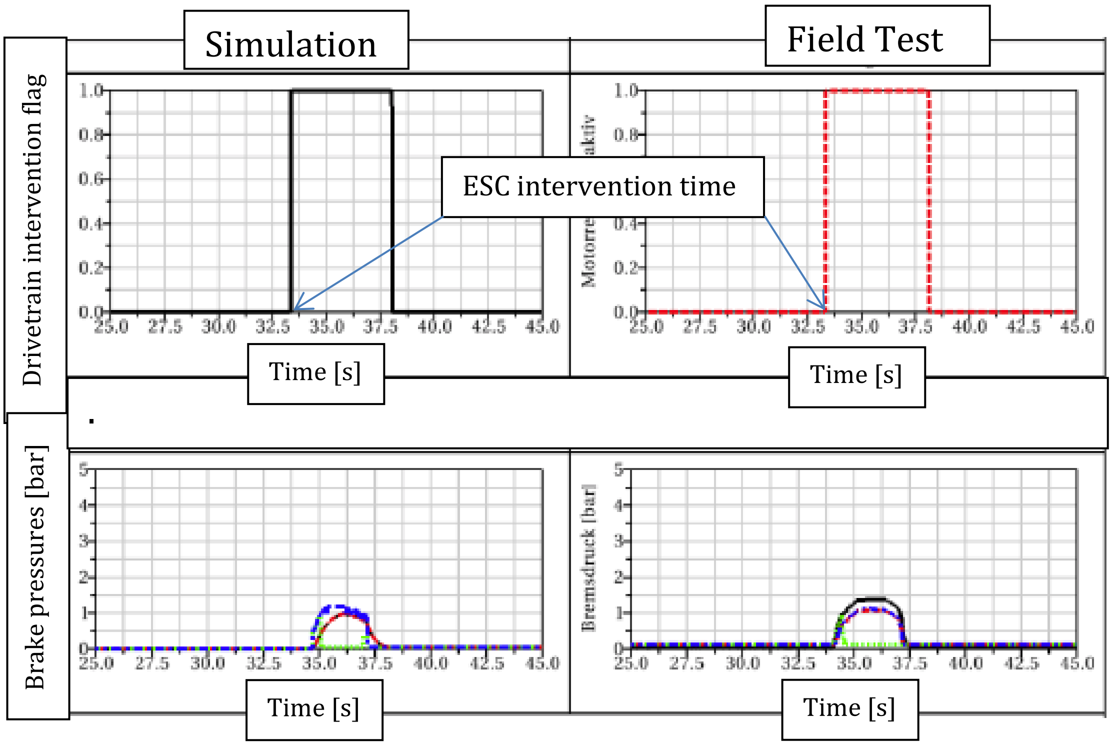

Figure 4: ESC system output (drivetrain interventions and desired brake torque), Example for comparison of simulation (left) and measurement (right)

NOTE The ESC intervention time may already be substantially different in simulation and measurement when only slight differences in vehicle velocity occur between simulation and measurement. For this reason, the intervention steering wheel angle serves as the reference value for the comparison.

9.3.2 Vehicle behaviour after ESC intervention

For comparing the vehicle behaviour after the intervention of the electronic stability system, the first peak values of lateral acceleration and yaw velocity after the ESC intervention time in the chosen measurement are compared to those recorded in the simulation, see Figure 5.

For both driving directions and for “ESC ON”, the deviation of the derived characteristic values between the simulation results and the measurement results should not exceed the values specified in Annex A, Table A.1.

For comparing the maximum values of yaw velocity and lateral acceleration after the intervention time, graphs of these values versus steering wheel angle may also be used, see Figures 6 and 7. This representation may also serve to compare graphically the values of intervention steering wheel angle and intervention yaw velocity in simulation and field test, see Figure 6.

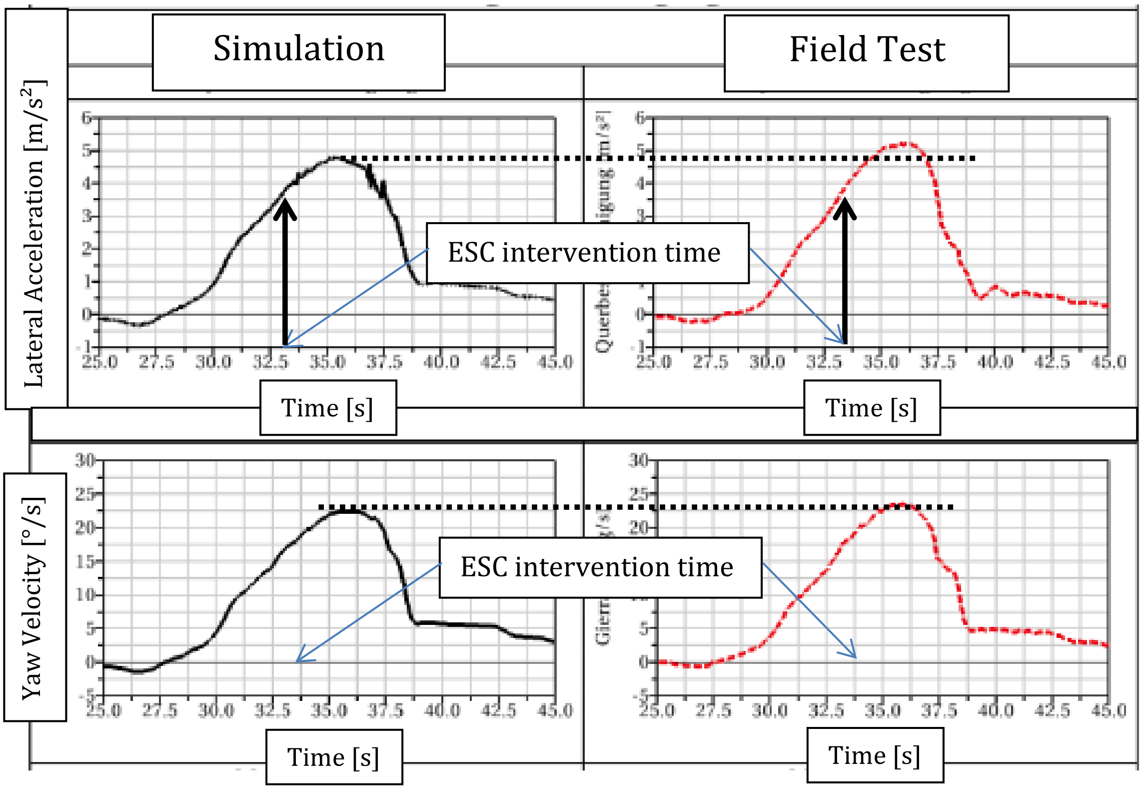

Figure 5: Yaw velocity and lateral acceleration versus time for measured steer input
Example for comparison of simulation (left) and measurement (right), “ESC ON”

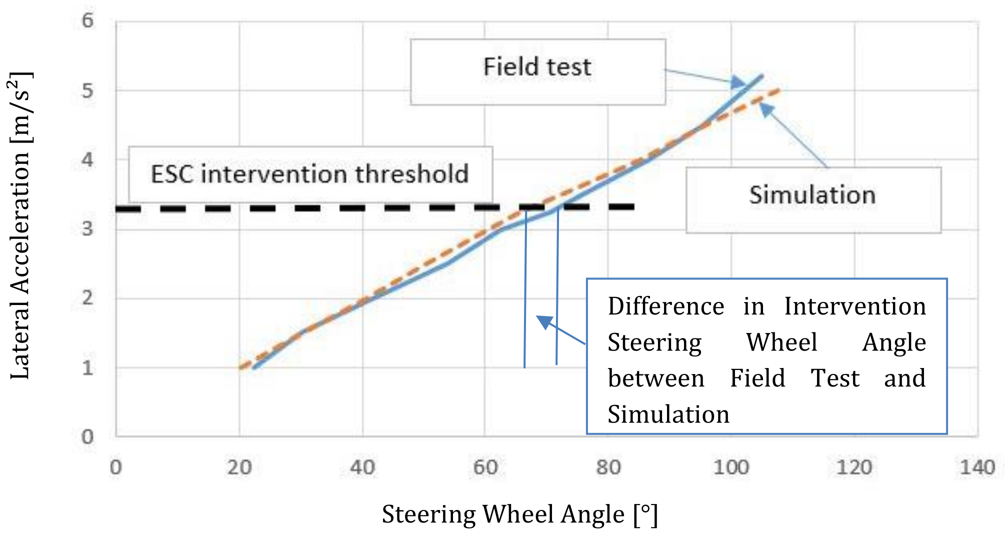

Figure 6: Lateral acceleration versus steering wheel angle for measured steer input
Example for comparison of simulation (left) and measurement (right), “ESC ON”

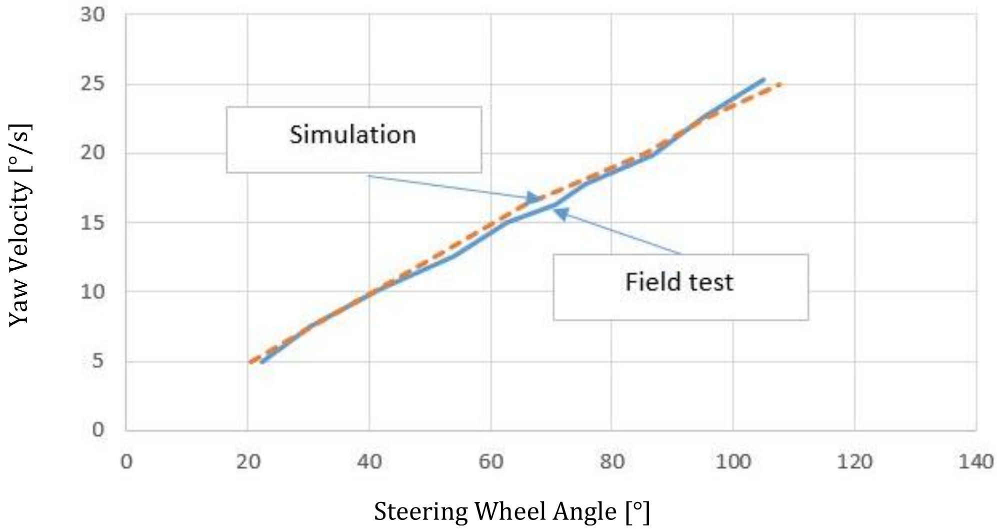

Figure 7: Yaw velocity versus steering wheel angle for measured steer input
Example for comparison of simulation (left) and measurement (right), “ESC ON”

9.4 ESC safety margin gained from the measurements with and without ESC

The difference between the entrance speeds with “ESC ON” and “ESC OFF” may serve as a characteristic value for the safety margin of the electronic stability system.

The maximum entrance speed derived from the simulation should be within +/- 5 km/h of the respective field test results both with “ESC ON” and “ESC OFF”, see Annex A.

Annex A
(normative)

Validation report

A.1 General

The test report for general data shall be as given in ISO 15037-2:2002, Annex A.

A.2 Test conditions

The test report for test conditions shall be as given in ISO 15037-2:2002, Annex B.

A.3 Tolerance boundaries

Table A.1 shows the recommended values for proving good correlation between the simulation model and the field test results.

Table A.1: Recommended maximum deviation between simulation and measurement

Value	Recommended maximum deviation
Tests with Electronic Stability Control “OFF”:	
Lateral acceleration of first wheel lift-off	+/- 10%
Mean relative deviation of lateral acceleration and yaw velocity, “ESC OFF”	+/- 10%
Maximum entrance speed, “ESC OFF”	+/- 5 km/h
Tests with Electronic Stability Control “ON”:	
Intervention lateral acceleration	+/- 10%
Intervention yaw velocity	+/- 10%
First peak value of yaw velocity	+/- 20%
First peak value of lateral acceleration	+/- 20%
Maximum brake torque	+/- 25%
Maximum entrance speed, “ESC ON”	+/- 5 km/h

