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

Véhicule utilitaires lourds et autobus — Simulation et validation dynamique des véhicules — Essai en courbe fermée

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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.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 — Closing-curve test

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 closing-curve tests as specified in ISO 11026. The purpose of the validation is to demonstrate that the vehicle dynamics simulation, combined with an integrated electronic stability control (ESC) system, can predict the roll and yaw stability behaviour of a physical vehicle, including the ESC system interventions, during a closing-curve test. 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 software code generated from the same source as for the ECU in the real vehicle. 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 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 11026, *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 behavior*

3 Terms and definitions

For the purpose of this standard, the terms and definitions given in ISO 3833, ISO 8855, ISO 15037-2, ISO 11026, ISO 19585 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
software-in-the-loop
SiL
method of integrating the ESC system into the simulation using a software code generated from the same source as for the vehicle ECU

3.2
hardware-in-the-loop
HiL
method of integrating the ESC system into the simulation by incorporating both the vehicle model and the ECU hardware into a HiL 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* (3.3)

3.5
intervention yaw velocity
yaw velocity at the *ESC intervention time* (3.3)

3.6
intervention lateral acceleration
lateral acceleration at the *ESC intervention time* (3.3)

3.7
maximum initial velocity
maximum initial driving condition velocity for the test path at which no subsequent wheel lift-off occurs during the test and at which the vehicle maintains the intended trajectory

4 Principle

The test method defined in ISO 11026 serves to determine the rollover stability of heavy commercial vehicles and buses as defined in ISO 3833. The test method is designed for vehicles equipped with an electronic stability system (ESC).

Within this document, the purpose of the closing-curve test validation is to demonstrate that a vehicle model can predict the vehicle stability behaviour within specified tolerances. The vehicle model is used to simulate a specific existing vehicle, which is also tested physically, using the test method specified in ISO 11026. Measurement results are used to define reference curves and characteristic values, and the respective simulation results are compared to analyse the deviation between physical test and simulation.

Prior to the validation of the vehicle model for the closing-curve test, a validation for steady-state cornering according to ISO 19585 shall be conducted. In addition to this basic validation, the validation done according to this document serves to demonstrate that the vehicle model correctly predicts wheel lift-off during the closing curve test and that ESC interventions are represented correctly by the simulation.

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 (or alternatively the ESC sensor position) of the first vehicle unit. This provision overrides the similar provision of ISO 15037-2. Measurement requirements shall be taken from ISO 11026 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;

— yaw velocity, $\dot{\psi}$;

— intervention flags (ESC output values) for both drivetrain and brake control;

— desired engine torque limit (ESC output values);

— desired brake torques or desired brake pressures (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.

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

For vehicles with an electrical actuation of the brakes, the desired brake torques shall be determined instead of the desired brake pressures.

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 vehicle model capable of calculating variables of interest for the test procedures being simulated. In this document, the vehicle model is used to simulate the closing-curve test method described in 7.2 and to provide calculated values of the variables of interest from Clause 5.

Prior to the validation of the vehicle model for the closing-curve test, a validation for steady-state cornering according to ISO 19585 shall be conducted. Correspondingly, all definitions of the simulation model parameters and requirements included in ISO 19585:2019, Clause 6, shall apply, together with the following additional specifications for the closing-curve test and the interventions of the ESC system.

6.2 Basic vehicle parameters

The basic vehicle parameters of ISO 19585:2019, 6.2, shall apply.

6.3 Estimated vehicle parameters

The estimated vehicle parameters of ISO 19585:2019, 6.2, 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 ±20 % during the validation process.

6.3.2 Tyre force characteristics

In addition to the definitions specified for the tyre lateral force characteristics in ISO 19585:2019, 6.2, the tyre model shall be capable of representing the tyre transient force behaviour.

The tyre model of the vehicle model shall include the tyre longitudinal force characteristics and a representation of the combined lateral and longitudinal slip behaviour in order that the ESC system brake intervention effects can be simulated. It is recommended that (on a dry and even road surface) the deviation of the gradient around zero of the tyre longitudinal force versus longitudinal slip used in the tyre model and the curves of the tyre measurement should not exceed ±20 %. The maximum value of the longitudinal force of the tyre model should be within ±10 % of the measured value. 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 Alternatively, a comparison of the wheel speed signals observed during the ESC interventions in physical test and in simulation can serve for proving correct representation of the longitudinal tyre force characteristics.

6.3.3 Damper characteristics

The initial values of the axle dampers shall be derived from measurements or design data and should not be altered more than ±10 % during the validation process. Where the vehicle model includes a separate cabin mass the same requirements apply for the cabin dampers.

NOTE During the closing curve test the damper velocities are relatively low and therefore, it is possible for a linear approximation of the damper characteristics to be sufficient for the validation.

6.4 Electronic stability control

The electronic stability control used in the vehicle 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 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 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 vehicle model. Typically, the data submitted from the vehicle 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 vehicle 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 torques and brake pressures. It is recommended that additional parameter values are given from the system code to the vehicle model, which serve to monitor the correct functionality of the system code in the simulation loop.

When using the HiL method to combine the ESC system with the vehicle model, both the vehicle model and the hardware of the ECU are integrated into a HiL test bench. To enable the correct functionality of the ECU on the test bench, an additional exchange between the ECU and the vehicle simulation model will be necessary. It shall be documented that the ECU was in an error free status when conducting the simulation using the HiL method.

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

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 manoeuvres with the vehicle model prior to the closing-curve test, such as accelerating and braking straight ahead. It is recommended to monitor the “learnt” values such as vehicle mass as output values of the ESC. When using the SiL method, these parameters may also be entered manually during the initialization phase of the SiL code in the simulation.

6.5 Braking system

For representing correctly the braking interventions of the electronic stability control, the vehicle model shall include a model of the braking system. This model shall contain the dynamic response of the vehicle brakes to the brake torques or brake pressures desired by the electronic stability system. Furthermore, it shall contain a representation of the braking forces at the wheels (e.g. including the braking force distribution between the vehicle axles). For vehicle combinations, this includes the braking system of the trailer(s).

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

A comparison of the physical test and simulation results for braking straight ahead with maximum brake torque, in accordance with ISO16552:2014, is recommended for proving the correct functionality of the braking system (including the ABS) within the vehicle model.

6.6 Additional model requirements

The additional model requirements of ISO 19585:2019, 6.2, shall apply.

7 Physical testing

7.1 General

The physical vehicle of interest shall be tested using the method specified in ISO 11026. 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, a minimum of three valid test runs shall be conducted. The criteria for a valid test run are those given in ISO 11026. The loading condition definitions of ISO 11026 shall apply.

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. The sampling and filtering of the measurement signals shall comply with the definitions in ISO 15037-2.

7.2 Test method

It is recommended to use the test path defined in ISO 11026 that results in a 2m/s^3 jerk at an initial driving condition velocity of 60 km/h for validation of the vehicle model. Other test paths specified in ISO 11026 may be used additionally and/or alternatively. A series of tests at incremental initial driving condition velocities shall be conducted on the chosen test path(s) commencing with a velocity at which no ESC intervention occurs. The initial driving condition velocity shall be increased in steps of no more than 5 km/h until the recorded wheel speed sensor signals indicate the lift-off of an inner wheel, or severe oversteer or understeer conditions to cause the vehicle reference point to deviate from the defined test path more than ±0,5 m as specified in ISO 11026. This initial driving condition velocity shall be reported as the maximum initial driving condition velocity. Should wheel lift-off occur, the lateral acceleration at which the first inner wheel lifts, and the order of the wheel lift-off sequence, shall be reported.

As electronic stability 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 shall be reported together with the steering wheel velocity.

7.3 Evaluation of test results

The time histories of the variables listed in Clause 5 shall be plotted for each valid test run.

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 performed using the same test method parameters employed for the physical vehicle tests and shall output the characteristic variables and values described in 7.3.

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 test path from ISO 11026) as used in the physical 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, the measured initial longitudinal vehicle velocity can be used as input for the initial longitudinal velocity of the simulation model.

8.2 Data recording

The output of the simulation model shall be at a frequency not less than that of the sampling rate 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 simulation software;

— identification (internal name) of the vehicle model;

— name and version number of the tyre model;

— name and version number of the esc stability control;

— ESC parameter sheet;

— list and contents of input files used.

9 Comparison of simulation and physical tests

9.1 General

For comparing curves of the simulated and measured vehicle behaviour, at least one physical test result shall be chosen. The chosen test run shall include a braking system intervention of the electronic stability control, 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 curves for other initial vehicle velocities additionally. 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 physical test shall be reported.

9.2 Dynamic vehicle behaviour without ESC

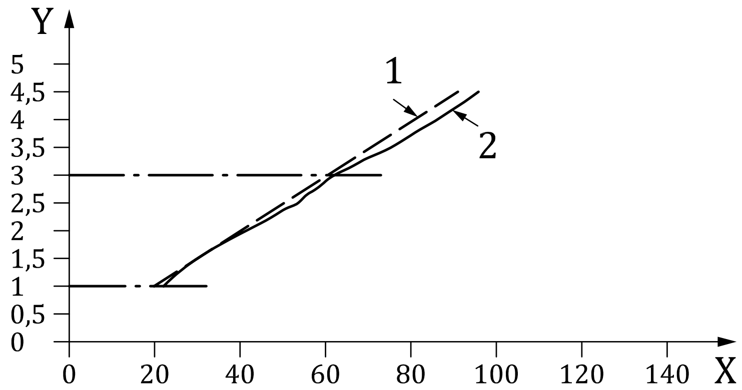
9.2.1 Wheel lift-off

The order of inner wheel lift-off observed with the vehicle model should be the same as that reported from the physical test. The lateral acceleration at which the first wheel lift-off occurs in simulation should be within the tolerance specified in Table A.1.

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 physical 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 vehicle model with the results from the physical tests, see Figures 1 and 2. For both turn directions and for "ESC OFF", the deviation of the characteristic values gained from simulation and from the physical test should not exceed the values specified in 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 physical tests and the simulation, see Figure 3.



Key

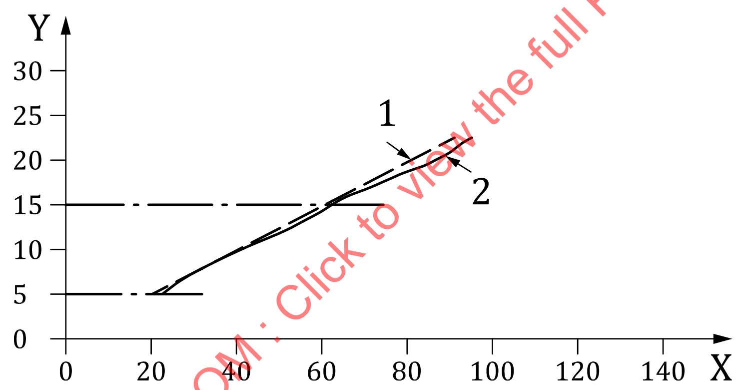
X steering wheel angle [°]

Y lateral acceleration [m/s^2]

1 simulation

2 physical test

Figure 1 — Lateral acceleration versus steering wheel angle, "ESC OFF", example for comparison of simulation and physical test



Key

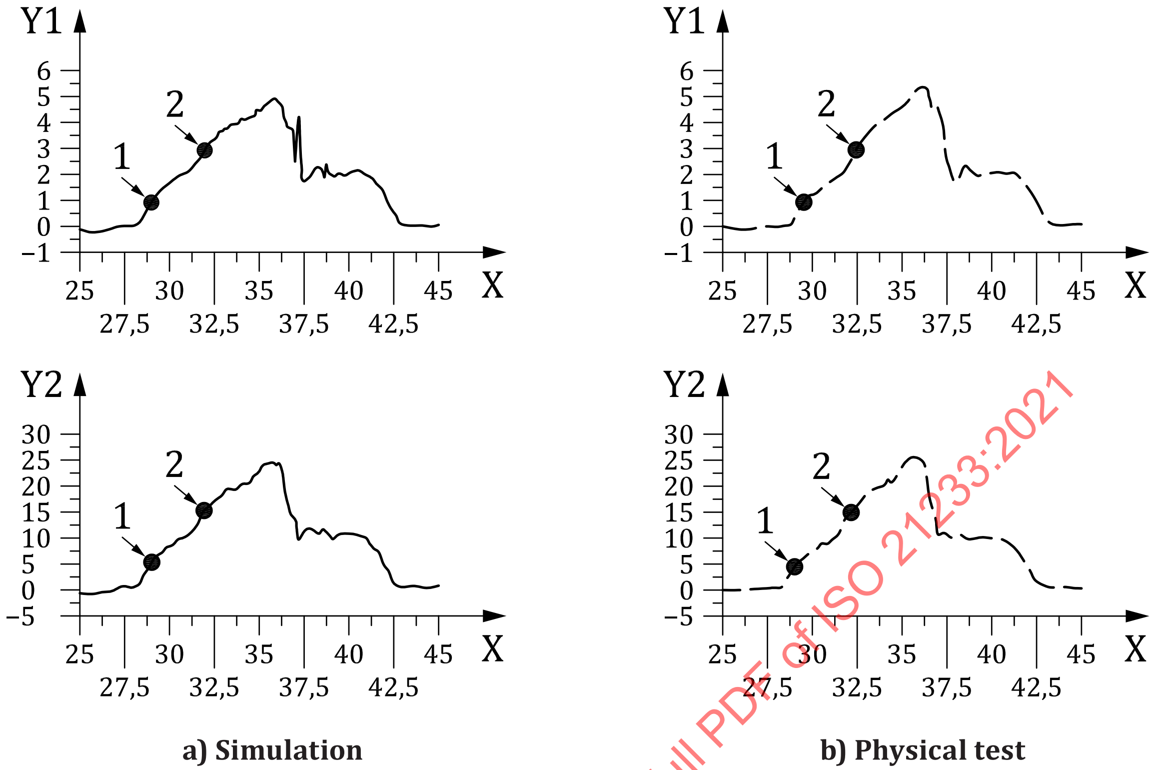
X steering wheel angle [°]

Y yaw velocity [°/s]

1 simulation

2 physical test

Figure 2 — Yaw velocity versus steering wheel angle, "ESC OFF", example for comparison of simulation and physical test



Key

X time [s]

Y1 lateral acceleration [m/s²]

Y2 yaw velocity [°/s]

1 point in time for a lateral acceleration of 1 m/s²

2 point in time for a lateral acceleration of 3 m/s²

Figure 3 — Yaw velocity and lateral acceleration versus time (simulation with measured steer input), example for comparison of simulation (left) and physical test (right), "ESC OFF"

The curves from simulation and physical testing are compared within a steering wheel angle envelope whose upper and lower boundaries are those at which the physical test vehicle achieves 1 m/s² and 3 m/s² respectively, 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 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:

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

where

$a_{y,s,i}$ is the lateral acceleration value from simulation for the chosen value of the steering wheel angle;

$a_{y,m,i}$ is the lateral acceleration value from measurement for the same chosen value of the steering wheel angle;

and

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

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

9.3 Dynamic vehicle behaviour with ESC

For the test series with the ESC switched on, characteristic values of yaw velocity and lateral acceleration obtained from the measurement and the simulation are compared.

9.3.1 ESC intervention

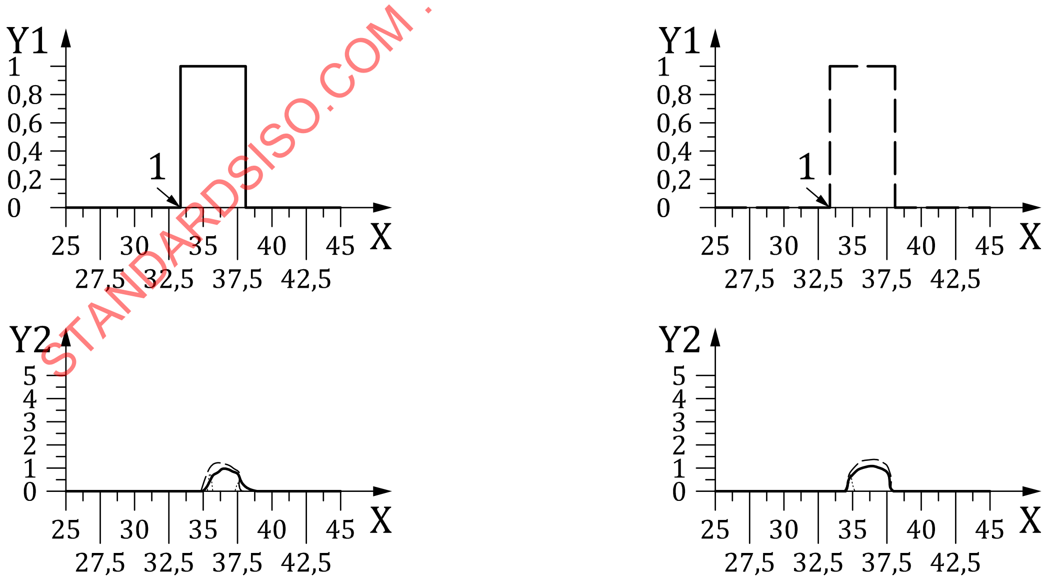
For comparing the interventions of the ESC system implemented in the vehicle model with the system interventions during the chosen representative physical test, the graphs of the intervention flags and desired brake torques (or desired brake pressures) of the electronic stability control versus time shall serve as a basis, see Figure 4. For proving good correlation, the following criteria should be fulfilled, see Table A.1:

— the simulation should show the same type of intervention (either rollover stability control or yaw stability control) as the physical test and should show the ESC drivetrain interventions;

— the lateral acceleration and the yaw velocity at the ESC intervention time in the simulation should be within ±5 % of the respective values during the physical test;

— the maximum desired brake torques or brake pressures of the first ESC braking intervention in the simulation should be within ±25% of the respective values during the physical test.

The figures within this document show a comparison of the desired brake pressures for a vehicle with a pneumatic braking system. For vehicles with an electrical actuation of the brakes, the desired brake torques shall be used for the comparison.



a) Simulation

b) Physical test