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Passenger cars — Validation of vehicle dynamic simulation — Sine with dwell stability control testing

Voitures particulières - Simulation et validation dynamique des véhicules - Essais de contrôle de la stabilité en sinus avec palier

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Foreword

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

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The committee responsible for this document is ISO/TC 22, *Road vehicles*, Subcommittee SC 33, *Vehicle dynamics and chassis components*.

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.

Passenger cars — Validation of vehicle dynamic simulation — Sine with dwell stability control testing

1 Scope

This document specifies a method for comparing computer simulation results from a vehicle mathematical model to test data measured for an existing vehicle undergoing sine with dwell tests that are typically used to evaluate the performance of an electronic stability control (ESC) system. 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.

NOTE The sine with dwell test method described in this document is based on the test method specified in regulations USA FMVSS 126 and UN/ECE Regulation No. 13-H.

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

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 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:

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

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

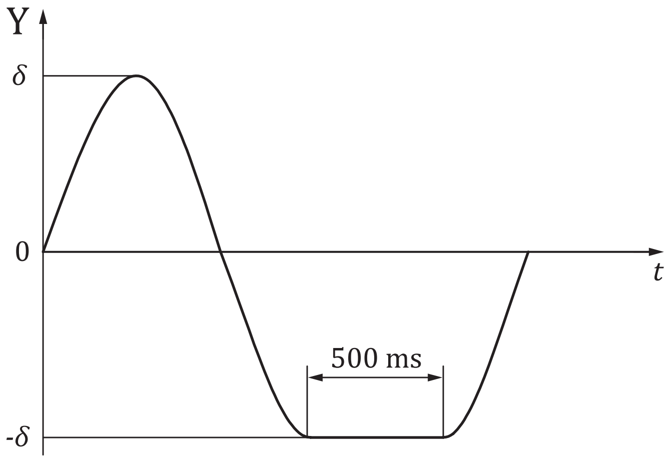
3.1
simulation
calculation of motion variables of a vehicle from equations in a mathematical model of the vehicle system

3.2
simulation tool
simulation (3.1) environment including software, model, input data, and hardware in the case of hardware-in-the-loop simulation

3.3
electronic stability control system
ESC system
control system that intervenes to maintain directional stability of vehicle and responsiveness on steering input

3.4
sine with dwell test
test in which the vehicle is steered by a robot using a steering pattern of a sine wave at a frequency of 0,7 Hz with a delay of 500 ms beginning at the second peak amplitude

Note 1 to entry: See Figure 1.



Key

Y steering-wheel angle

t time

Figure 1 — Steering-wheel input for a sine with dwell test

3.5
sine with dwell test series
series of *sine with dwell tests* (3.4) in which the amplitude of the steering pattern is increased with each test

3.6
beginning of steer
BOS
time at which the steering begins for a *sine with dwell test* (3.4)

3.7
completion of steer
COS
time at which the steering is completed for a *sine with dwell test* (3.4)

3.8
ESC system performance standard
published standard, typically issued by a regulatory organization, that defines *ESC system* (3.3) performance requirements using a *sine with dwell test* (3.4) series

Note 1 to entry: For example, UN/ECE Regulation No. 13-H or USA FMVSS 126.

4 Principle

A sine with dwell test sequence is used to evaluate the behaviour of a vehicle with ESC. In this sequence, the vehicle is subjected to two series of tests that are run using a steering pattern of sine with dwell as shown in Figure 1. One series uses counterclockwise steering for the first half cycle, and the other series uses clockwise steering for the first half cycle.

Within this document, the purpose of the test is to demonstrate that a simulation tool can predict vehicle behaviour in the sine with dwell test sequence as described in a specific ESC system performance standard.

A comparison is made between measured and simulated behaviour using samples taken at a few specified points during each run, using tolerances specified in this document.

A simulation tool being evaluated for use with the sine with dwell test should first be validated for steady-state circular driving behaviour as specified in ISO 19364. A simulation tool that cannot reproduce steady-turning behaviour should not be considered for use in simulating the sine with dwell response.

5 Variables

The following variables shall be measured from the physical testing and obtained from the simulation tool:

— steering-wheel angle;

— yaw rate;

— lateral acceleration.

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 a sine with dwell test series as specified in the ESC system performance standard of interest.

The procedure for obtaining input data from experiments may differ for simulation tools; however, the input data shall not be manipulated for better correlation. However, 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, outriggers, 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 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. Large longitudinal slip ratios might be generated as a result of intervention of the ESC. 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. Note in particular that 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 are typically encountered in a sine with dwell test series.

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 and C) tests.

The model shall cover the full nonlinear range encountered in the sine with dwell 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 should cover the range of suspension jounce and rebound rate encountered in the sine with dwell tests.

6.5 Steering system

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

The sine with dwell test requires that a robot provide 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 sine with dwell tests.

NOTE Because 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 displacement inputs that do not match the intended displacements. 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 80 km/h.

6.7 Brake system

The vehicle brake model shall include the actuators and dynamic response properties that affect the interventions generated by the ESC. Accurate prediction of the dynamic interaction of the brake torque and the controls from the ESC, including the sequence of brake torque application, are critical for successful simulation of sine with dwell testing.

6.8 Powertrain

In the sine with dwell manoeuvre covered in this document, the vehicle is coasting in the highest gear from an initial speed of 80 km/h. 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 ESC intervention 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 the coast-down condition of this manoeuvre; 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 sine with dwell manoeuvre covered in this document shall be included in the simulated version. In particular, the representation of the ESC system is critical to the validity of the simulation.

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, etc. in the simulation should match the physical test setup.

6.11 Driver controls

The simulation tool shall be capable of providing steering control for the sine with dwell test.

7 Physical testing

7.1 General

An existing vehicle of interest shall be tested using the sine with dwell test sequence as defined in the applicable ESC system performance standard. The applicable ESC system performance standard shall be identified in the report.

NOTE This document does not define all of the details of the testing procedure; these details are obtained from the applicable ESC system performance standard. This subclause does describe the parts of the test procedure that are typically simulated.

7.2 Conditioning the vehicle

The vehicle is prepared as described in the applicable ESC system performance standard. This involves loading as needed with fuel and ballast, setting tire pressures, possibly installing outriggers to prevent rollover, and other steps covered in published test descriptions. Once equipped, the vehicle is typically exercised to condition the tires and brakes.

7.3 Slowly increasing steer tests

7.3.1 Slowly increasing steer procedure

The vehicle is subjected to two series of runs of the slowly increasing steer test using a constant vehicle speed of (80 ± 2) km/h and a steering pattern that increases by 13,5°/s until a lateral acceleration of approximately 0,5 g is obtained. Three repetitions are performed for each test series. One series uses counterclockwise steering, and the other series uses clockwise steering.

7.3.2 Reference steering wheel angle “A”

The quantity “A” is determined from the slowly increasing steer tests, where “A” is the steering-wheel angle in degrees that produces a steady-state lateral acceleration (corrected using methods specified in the ESC system performance standard) of 0,3 g for the test vehicle. “A” is calculated by linear regression to the nearest 0,1°, from each of the six slowly increasing steer tests. The absolute values of the six “A” values are averaged and the result is rounded to the nearest 0,1° to produce the final quantity, “A”, used below.

7.4 Sine with dwell test series

7.4.1 Sine with dwell steering pattern

The vehicle is subjected to two series of test runs using a steering pattern of sine with dwell (see Figure 1). One series uses counterclockwise steering for the first half cycle and the other series uses clockwise steering for the first half cycle.

7.4.2 Speed

The steering motion is initiated with the vehicle coasting in high gear at (80 ± 2) km/h.

7.4.3 Steering amplitude

The steering-wheel angle amplitude for the initial run of each series is 1,5 A, where “A” is the steering-wheel angle determined in 7.3.2.

In each series of test runs, the steering amplitude is increased from run to run by 0,5 A, provided that no such run will result in a steering amplitude greater than the final run amplitude specified in 7.4.4.

7.4.4 Steering amplitude for final runs in a series

The steering-wheel angle amplitude of the final run in each series is the greater of 6,5 A or 270°, provided the calculated magnitude of 6,5 A is less than or equal to 300°. If any 0,5 A increment, up to 6,5 A, is greater than 300°, the steering amplitude of the final run shall be 300°.

7.5 Data processing

7.5.1 Filtering and conditioning

Raw measurements of steering-wheel angle, steering-wheel rate, yaw rate, and lateral acceleration shall be filtered and conditioned as specified in the applicable ESC system performance standard.

7.5.2 Lateral displacement

The lateral displacement of the vehicle centre of gravity with respect to its initial straight path is obtained by double-integrating the lateral acceleration signal measured by a transducer located near the vehicle centre of gravity.

7.5.3 ESC system intervention

In each sine with dwell test, it shall be noted whether the ESC intervenes.

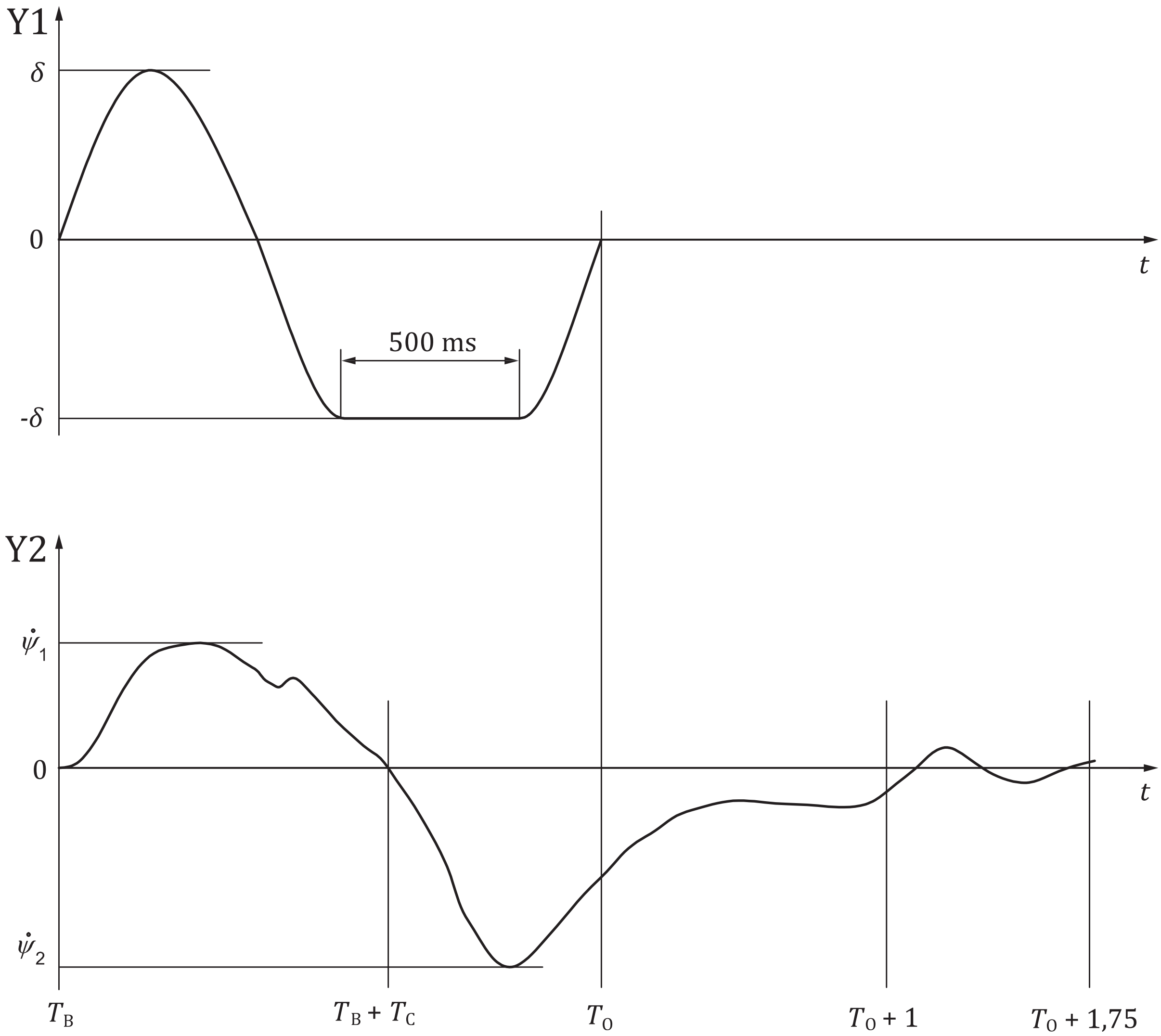
7.6 Performance requirements

7.6.1 Stability criteria

During each sine with dwell test, the vehicle shall satisfy the following two directional stability criteria, as specified in the applicable ESC system performance standard.

a) The value of yaw rate measured 1 second after the COS time shall not exceed 35 % of the value of the first peak value of yaw rate recorded after the steering-wheel angle changes sign ($\dot{\psi}_2$ in Figure 2).

b) The value of yaw rate measured 1,75 seconds after the COS time shall not exceed 20 % of the value of the first peak value of yaw rate recorded after the steering-wheel angle changes sign ($\dot{\psi}_2$ in Figure 2).



Key

Y1	steering-wheel angle
Y2	yaw rate
t	time
T_B	beginning of steer (BOS)
T_0	completion of steer (COS)
$T_B + T_C$	zero crossing for yaw rate

Figure 2 — Relationship between yaw rate information and sine with dwell steering-wheel angle input

7.6.2 Responsiveness criterion

During each sine with dwell test, the lateral displacement of the vehicle centre of gravity with respect to its initial straight path, computed 1,07 seconds after the BOS time, shall meet the requirement of the applicable ESC system performance standard.

8 Simulation

8.1 Limits on the simulated procedure

The simulation tool shall be configured to simulate the sine with dwell test series described in 7.4. Because the computer simulations are not sensitive to some factors of interest in physical testing, not all of the details specified in the ESC system performance standard apply.

Actions taken to prepare a physical vehicle for testing, such as checking tire pressures, driving manoeuvres to warm up the tires and brakes, and so on, might not be needed for the simulation tool.

8.2 Slowly increasing steer tests

For the purpose of this document, the same steering-wheel angle inputs are used for both simulation and physical testing.

The reference steering-wheel angle amplitude “A” may be obtained from the physical testing results or from simulation of the slowly increasing steer test. In either case, the same amplitude “A” shall be used for both simulation and physical tests in the sine with dwell series described in 7.4.

8.3 Sine with dwell test series

The sine with dwell test series described in 7.4 is simulated.

8.4 Data processing

8.4.1 Filtering and conditioning

Time histories of the variables of interest (see Clause 5) should be filtered in the same manner as the measured signals.

NOTE ESC system performance standards typically specify phaseless low-pass filtering to reduce measurement noise yet not disturb the phase relationships between the measured variables. Time histories of the variables of interest from simulation are typically not subject to measurement noise, and therefore, the filtering and conditioning specified in the ESC system performance standard might not be necessary.

8.4.2 Lateral displacement

The lateral displacement of the vehicle centre of gravity with respect to its initial straight path is obtained by double-integrating the lateral acceleration of the vehicle centre of gravity, corresponding to the signal defined for the test data in 7.5.2.

Vehicle simulation tools can typically provide the lateral coordinate of the vehicle centre of gravity without errors introduced by the approximations underlying the double-integration method specified in ESC system performance standard. However, for the purpose of simulation validation, the same definition of lateral displacement shall be used for test and simulation data.

9 Comparison between simulation and physical test results

9.1 Steady state turning validation

A simulation tool being evaluated for simulating tests specified in the ESC system performance standard shall also be validated for steady-state circular driving behaviour using the cross plots of steering-wheel angle, side slip angle, and roll angle versus lateral acceleration, as specified in ISO 19364. A tool that cannot reproduce steady-turning behaviour shall not be considered for use in simulating response for an ESC system performance standard.

9.2 Metrics from a sine with dwell series

9.2.1 General

The comparisons provided in this document can extend the validation to include the transient behaviour seen in the sine with dwell test. The simulation and physical test results are compared on the basis of values of variables recorded at the specific conditions described in 7.4, 7.5, 8.3 and 8.4.

9.2.2 Number of first test run in which ESC intervention occurs

The number of the first run in each of the two series of sine with dwell test runs (see 7.4) in which ESC intervention occurs for the physical testing shall match the corresponding number for the first run in the simulated series in which ESC intervention occurs, with a tolerance of ±1 test run number.

NOTE Conditions that lead to an ESC intervention are sensitive to test conditions that are not fully repeatable (speed, vibrations, wind, etc.), such that the first run in which intervention occurs can differ with repeated series of test runs. Agreement between the simulation and the physical testing is not expected to be better than the agreement between repeated series of physical test runs; therefore, first runs in which ESC intervention occurs may differ between a series of simulations and physical tests.

9.2.3 Test runs used for comparison

9.2.3.1 General

Metrics from the physical testing shall be compared to the corresponding metrics obtained from simulation for three of the test runs for each direction.

9.2.3.2 Last run without ESC intervention

Metrics are compared for the last run without intervention in both physical testing and simulation.

For example, if the first intervention in the series of physical test runs with initial counterclockwise steering occurs in the fourth run, and the first intervention in the simulated series occurs in the fifth run, then metrics shall be compared for the third run from each series.

9.2.3.3 First run with ESC intervention

Metrics are compared for the first run after intervention in both physical testing and simulation.

For example, if the first intervention in the series of physical test runs with initial counterclockwise steering occurs in the fourth run, and the first intervention in the simulated series occurs in the fifth run, then metrics shall be compared for the fifth run from each series.

9.2.3.4 Last run

Metrics are compared for the last run from each series.

9.2.4 Metric definitions and tolerances

9.2.4.1 General

Metrics obtained from the physical tests shall be subtracted from the corresponding metrics from the simulated tests. Those differences shall be compared to the tolerances listed in Table 1. The metrics named in the table are defined below.

Table 1 — Tolerances allowed between metrics obtained from physical testing and simulation

Metric	Test run	Tolerance
First peak yaw rate ($\dot{\psi}_1$ in Figure 2)	Last run without ESC intervention First run with ESC intervention Last run	±15 %
Time of yaw rate crossing zero (T_C in Figure 2)	Last run without ESC intervention First run with ESC intervention Last run	±0,1 s
Second peak yaw rate ($\dot{\psi}_2$ in Figure 2)	Last run without ESC intervention	±20 %
	First run with ESC intervention	±25 %
	Last run	±25 %
Lateral displacement of the vehicle C.G.	Last run without ESC intervention	±15 %
	First run with ESC intervention	±18 %
	Last run	±18 %

9.2.4.2 First peak yaw rate

The first peak yaw rate ($\dot{\psi}_1$ in Figure 2) is the first metric. The same tolerance is used for all three runs.

9.2.4.3 Time of yaw rate crossing zero

The value of the time of yaw rate crossing zero T_C after the BOS time is the second metric. The same tolerance is used for all three runs.

9.2.4.4 Second peak yaw rate

The second peak yaw rate from testing ($\dot{\psi}_2$ in Figure 2) is the third metric. Table 1 shows that a tighter tolerance is used for the run without ESC intervention.

9.2.4.5 Lateral displacement of the vehicle centre of gravity

In those test runs in which the lateral displacement of the vehicle centre of gravity with respect to its initial straight path is required by the applicable ESC performance standard to reach a specified level, the lateral displacement as determined from the test is used as the fourth metric. Table 1 shows that a tighter tolerance is used for the run without ESC intervention.

9.3 Validation of the simulation tool

If the number of the first test in each series in which ESC intervention occurs for the physical testing matches the corresponding number for the first test in the simulated series ±1 as specified in 9.2.2, and the conditions specified in 9.2.4 are met for the three tests used for comparison (see 9.2.3), then the simulation tool is considered valid for representing vehicle behaviour in the sine with dwell test.

10 Documentation

The ESC system performance standard that defines details of the test series shall be identified. 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 1176, *Road vehicles — Masses — Vocabulary and codes*

[2] ISO 2416, *Passenger cars — Mass distribution*

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[7] ISO 3833, *Road vehicles — Types — Terms and definitions*

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