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# Evaluation of electronic stability controllers using hardware-in-the-loop vehicle simulator

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**Abstract.** Hardware-in-the-loop (HiL) simulation is a very powerful tool to design, test and verify automotive control systems. However, well-validated and high degree of freedom vehicle models have to be utilized in these simulations in order to obtain realistic results. In this paper, a vehicle dynamics model developed in the Carsim Real Time program environment and its validation has been performed using experimental results. The developed Carsim real time model has been employed in the Tofas R&D hardware-in-the-loop simulator. Experimental and hardware-in-the-loop simulation results have been compared for the standard FMVSS No. 126 test and the results have been found to be in good agreement with each other. Two electronic stability control (ESC) algorithms, named the Basic ESC and the Integrated ESC, taken from the earlier work of the authors have been tested and evaluated in the hardware-in-the-loop simulator. Different evaluation methods have been formulated and used to compare these ESC algorithms. As a result, the Integrated ESC system has been shown superior performance as compared to the Basic ESC algorithm.

**Keywords**: hardware-in-the-loop simulator; electronic stability control; ESC evaluation

## 1. Introduction

Hardware-in-the-loop (HiL) simulation systems are frequently used to perform code changes, component tests and fault tests by major automotive companies and universities. Many different

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HiL vehicle dynamic simulation systems have been proposed in the literature. Sorniotti (2004) and Velardocchia and Sorniotti (2005) have developed a HiL test bench which contains whole braking system. It has been used for analysis and test of passive braking systems, anti-lock braking systems, electronic stability control systems and electro-hydraulic braking systems. A technical survey study has been conducted by Schuette and Waeltermann (2005) for HiL testing of vehicle dynamics controllers. In this paper, typical sensors and actuators, and related signals for vehicle dynamics control system have been introduced together with vehicle modeling for HiL systems. Also, application examples of HiL simulation for vehicle dynamics ECUs have been presented. In Gietelink *et al.* (2006), a vehicle hardware-in-the-loop simulation system has been proposed. This system has contained a full-scale vehicle and a chassis dynamometer in the simulation system. An adaptive cruise control and a forward collision warning system simulation have been conducted using this HiL test system and the results have been given. Zheng *et al.* (2006) have proposed a vehicle dynamics control system to track the desired vehicle behaviour using LQR based yaw moment control and sliding mode-based wheel slip control. The performance of the designed control system has been tested by HiL simulations. The hardware configuration of the proposed HiL system has been given in this paper. Kahraman *et al.* (2012) have proposed a HiL system for fully electric vehicles. The use of a HiL setup for ESC system development within a lab environment has been presented as a method of identifying and solving potential problems before road testing. Heidrich *et al.* (2013) have worked on a HiL platform for integrated testing of different configurations of brake systems, steering, and dynamic tire pressure control. They have obtained results for integrated chassis control with control allocation using this HiL platform. Peperhowe *et al.* (2013) have introduced another HiL test bench for efficient testing of vehicle dynamics control. They have proposed an approach that the vehicle dynamics parameters of interest are varied and their effects on performance are predicted before the road tests by using HiL simulations. Stahl and Leimbach (2014) have designed an active steering HiL test facility to enable assessment of the vehicle stability and safety performance. The details of the hardware and software parts of the HiL system have been given in this paper together with the HiL simulation results. Soltani and Assadian (2016) have described a HiL setup that includes real steering and brake smart actuator, high fidelity vehicle model, rapid control prototyping tool chain, and driver-in-the-loop capability. Test results for the brake caliper response, the closed loop slip control system and integrated vehicle dynamics control system have been given. Emirler *et al.* (2014) and Emirler *et al.* (2016) have proposed a HiL setup which can be used for testing the effect of changes in ESC algorithms in a lab setting. The effectiveness of the proposed HiL system has been shown by performing a $\mu$-split braking test.

An important vehicle dynamics control system named electronic stability control (ESC) system has become mandatory for new vehicles sold in North America and Europe. FMVSS No.126 test is used for homologation of ESC systems. Automotive companies customarily produce a large number of different variants of a vehicle platform as different models. Sometimes the main difference between models is just software changes. The acceptance of virtual homologation tests in a simulation environment containing a validated vehicle dynamics model will accelerate the product development process and costs. Moreover, hardware-in-the-loop vehicle simulators can also be employed for the development and evaluation of new ESC algorithms.

There is a need for a realistic and validated vehicle model that will run in real time for hardware-in-the-loop simulations. The simulator should send the same signals to the vehicle as the electronic control unit being tested. This type of simulator hardware is provided by specialized companies in this field. The parameters of the realistic vehicle model to be used in simulations

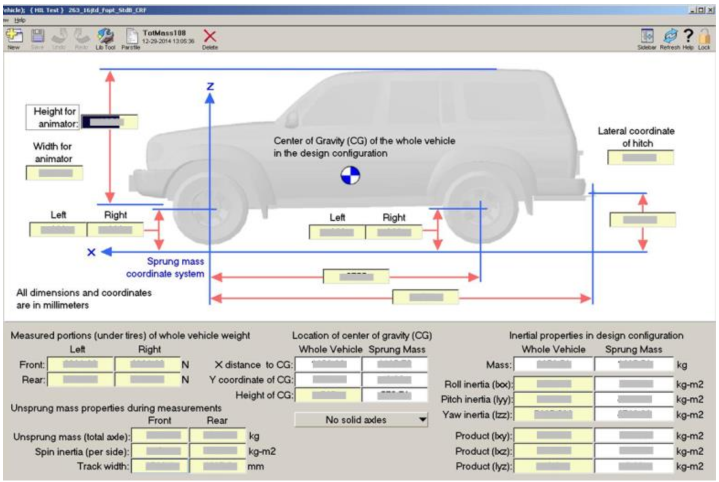


Fig. 1 The interface for vehicle dimensions in CarSim

need to be determined by a validation study. As a result of the validation study, it is desirable that the experimental and simulation results are matched with an acceptable level of fit.

This paper describes the development of a CarSim vehicle dynamics model validated for use in the Tofaş R&D hardware-in-the-loop vehicle simulator and its main focus is the evaluation of electronic stability control (ESC) algorithms using this vehicle simulator. FMVSS No.126 is employed for the acceptance of ESC systems. However, there is no evaluation criterion in the literature for ESC algorithms that pass the standard acceptance test (FMVSS No.126). The main contribution of this paper is to propose an electronic stability control evaluation score (ESC-ES) for ESC algorithms that pass the standard acceptance test. For this reason, two different evaluation scores named error-based ESC evaluation score (E-ESC-ES) and control-based ESC evaluation score (C-ESC-ES) are proposed. By using these scores, the overall evaluation score (ESC-ES) is calculated for comparing different ESC algorithms with each other.

The rest of the paper is organized as follows. In Section 2, CarSim vehicle dynamics model is introduced and the results of the model validation study are given. In Section 3, the hardware-in-the-loop vehicle simulator and its subsystems which can be used in the test of the ESC system are explained. In Section 4, the standard acceptance test (FMVSS No.126) is performed using this simulator and the results were compared with the road test results. Finally, the paper ends with conclusions given in Section 5.

## 2. CarSim vehicle dynamics model and validation study

In this section, the details of CarSim model for the light commercial vehicle were given first. Then, the simulation results were compared with the experimental results and the vehicle model was validated according to these results.

### *2.1 CarSim vehicle dynamics model*

CarSim vehicle dynamics program is a high degrees-of-freedom, reliable and Matlab/Simulink compatible software used by many universities, research institutes and automotive companies. In this study, firstly commercial light vehicle parameters such as weight, inertia, geometric dimensions, engine map, gear ratios, efficiencies, tire model coefficients and other related sub-system parameters were entered into CarSim software. Then, a model validation study was performed to obtain a realistic vehicle dynamics model.

Fig. 1 shows the interface for vehicle dimensions in CarSim. In order to simulate different loading conditions, several vehicle models have been created in CarSim as sub-models.

All the subsystems were created using the available parameters and then the first simulation studies were carried out in CarSim environment. After the first results were found reliable, various parameters were fine-tuned to get close actual vehicle results from the simulation model.

In CarSim, resistance forces acting on the vehicle can be modeled in detail. For example, Fig. 2 shows the interface where CarSim aerodynamic resistance coefficients are entered.

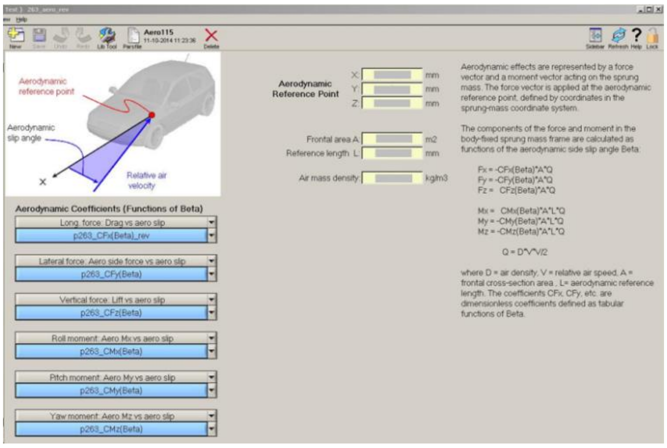


Fig. 2 The interface for aerodynamic resistance coefficients in CarSim

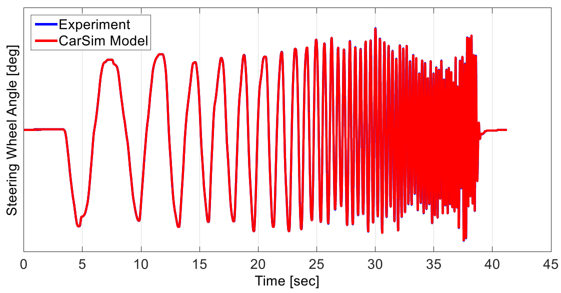


Fig. 3 Steering input in frequency sweep test

### *2.2 Model validation study*

Many standard road tests were conducted in model validation studies. Examples of these tests are constant radius turning test, ramp steering input test, double lane change test, slalom test and Sine-with-dwell test, FMVSS No. 126. Different tests were carried out to examine the different dynamic characteristics of the vehicle such as transient response, steady state response, and frequency response. In this paper, the frequency response results are given. Validation results of the other tests can be found in the authors' previous papers (Emirler *et al.* 2014, Emirler *et al.* 2016).

Fig. 3 shows the steering input for the frequency sweep test. The frequency of the sinusoidal steering input is increasing steadily. This experimental steering input was also generated in the simulation environment by entering it as an input to CarSim program together. Also, similar process was realized for the vehicle velocity which is collected during the actual test.

Fig. 4 show the frequency responses for the ratio of the vehicle lateral acceleration to the steering angle obtained by experiment and CarSim model. The gain and phase angle of the frequency responses show good fit for the experimental and the simulation results.

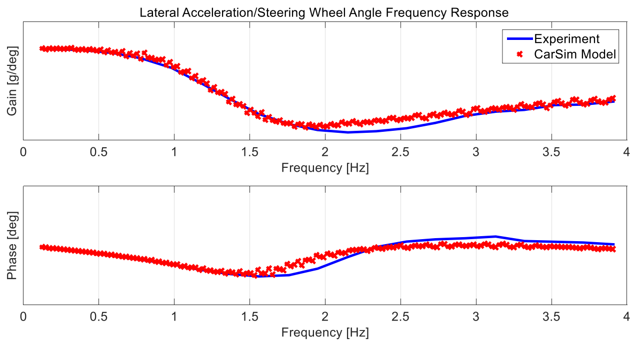


Fig. 4 Lateral acceleration/steering angle frequency response

In Fig. 5, the frequency response for the ratio for yaw rate to the steering angle is given as gain and phase plots. The results of the experiments and simulations follow a similar characteristic and overlap at an acceptable level.

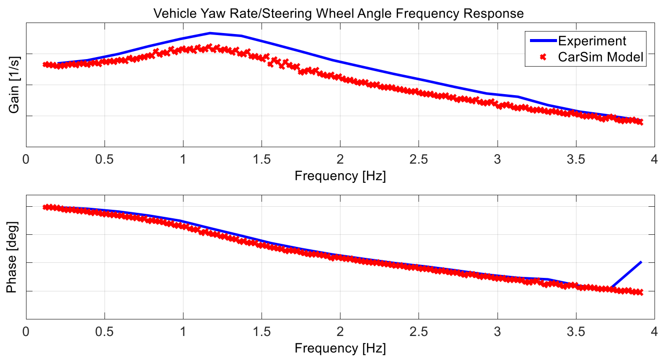


Fig. 5 Yaw rate/steering angle frequency response

By looking at the overlap of all the test and simulation results, CarSim vehicle model has been found as suitable for capturing real vehicle dynamics and it has been employed in ESC test and evaluation studies.

## 3. Hardware-in-the-loop vehicle simulator

The validated Carsim vehicle model is run in real time on Tofaş hardware-in-the-loop vehicle simulator. A dSPACE EcoLine Simulator is used as a hardware-in-the-loop simulation platform. Simulator uses a wheel signal generator circuit, a Hall-effect sensor-based valve position sensing unit, an ESC electro-hydraulic valve control unit, a yaw rate sensor and a steering angle sensor.

The real-time simulation can be controlled and the change of important parameters during the simulation can be monitored by an interface which is designed using dSPACE Control Desk. This interface is shown in Fig. 6.

The hardware-in-the-loop vehicle simulator is shown schematically in Fig. 7. The actual hardware used in the HIL testing is the ESC control unit. The valve signal read unit is used to read the valve command signals generated by this unit. Other vehicle electrical systems like the cockpit are used to check that the system functions properly. Simulation results for ESC testing obtained by hardware-in-the-loop simulator gave almost the same results with offline simulations.

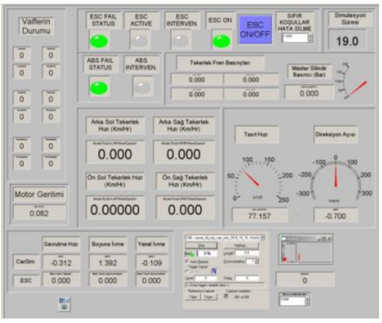

Fig. 6 The interface of hardware-in-the-loop vehicle simulator

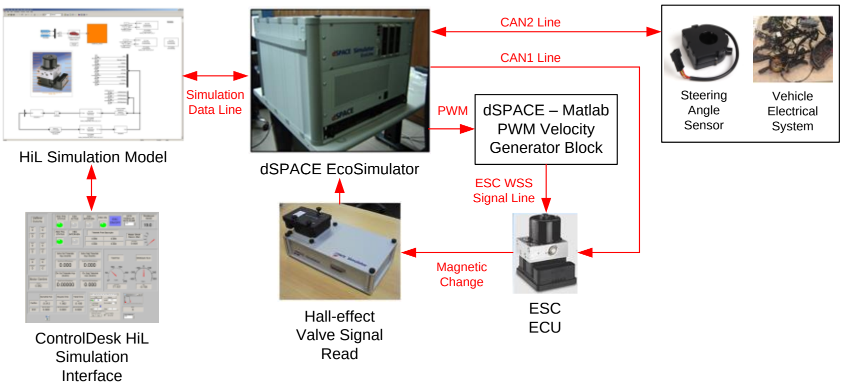


Fig. 7 Tofaş hardware-in-the-loop vehicle simulator for ESC testing

## 4. Evaluation of electronic stability controllers

### *4.1 ESC acceptance criterion*

FMVSS No. 126 is an ESC homologation test used both in the US and in the European Union (by name ECE 13-H regulation) (NHTSA 2007, UNECE 2009). The stability of the vehicle lateral dynamics is tested with this standard test. In the FMVSS No. 126 test, the steering angle, $\delta$, which makes the vehicle lateral acceleration value 0.3 g, is detected when the vehicle turns at 80 km/h. Then the FMVSS No. 126 test is started using this steering input. Fig. 8 shows the steering input used in this test. The dwell time is 500 milliseconds.

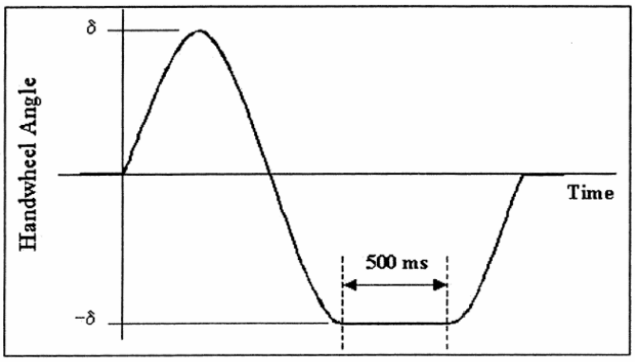


Fig. 8 Sine-with-dwell steering input used in FMVSS No.126 test (NHTSA 2007)

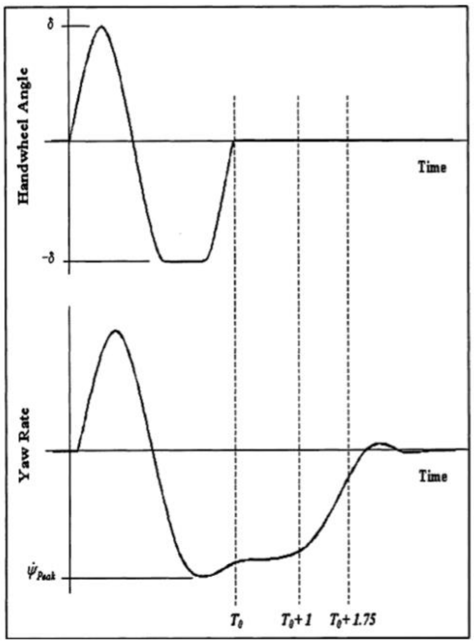


Fig. 9 Vehicle yaw rate change with respect to sine-with-dwell type steering angle input (NHTSA 2007)

According to FMVSS No.126 test, a sine-with-dwell type steering angle input with amplitude of $\delta$ and with frequency of 0.7 Hz is applied in the first maneuver. After the completion of this first maneuver, the values of the vehicle yaw rate and lateral displacement at 1 sec and 1.75 sec are compared with the standard values. If the results are appropriate, the amplitude of steering angle is increased by 0.5$\delta$ and the sine-with-dwell type steering input maneuver is repeated until the steering input reaches either 6.5δ or 300 degrees. If the standard values are obtained from all these repeated maneuvers, it means that the vehicle has passed the standard ESC test.

According to the test, the value of the vehicle yaw rate, measured 1 second after the completion of Sine-with-dwell type steering input, should be less than 35% of the first peak value of the vehicle yaw rate. The vehicle yaw rate at 1.75 s from completion of the test should be less than 20% of the initial peak value. Again, according to the test, for vehicles with a weight of less than 3500 kg, the amount of lateral displacement relative to the first linear path of the vehicle should be below 1.83 m after 1.07 seconds from the start of the test. The flow diagram of the FMVSS No.126 test in CarSim is shown in Fig. 10.

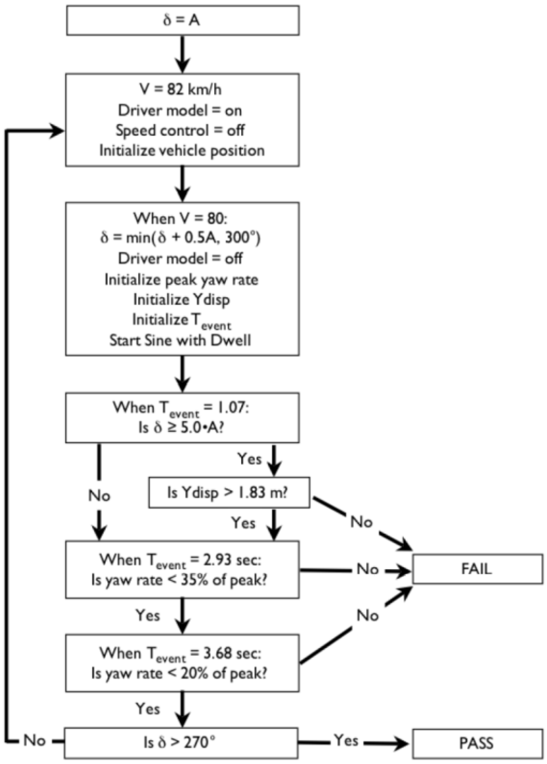


Fig. 10 The flow chart of FMVSS No. 126 test (CarSim 2011)

The simulation results shown in Figs. 11-15 were obtained with the hardware-in-the-loop vehicle simulator. The vehicle steering input and the velocity profile were collected in a real FMVSS No. 126 road test and these values were entered to CarSim vehicle model. Fig. 11 shows the steering angle input profile applied to the vehicle simulator. It can be seen that sine-with-dwell type steering input was applied with increasing amplitudes.

Fig. 12 shows the velocity profile obtained from the actual road test and the simulator. The vehicle model follows the actual vehicle velocity decrease profile. However, the velocity increase profile after single braking does not respond very well. It's slower. This situation can be solved by the proper parameter settings.

In Fig. 13, the vehicle yaw rate change is given for the road test and the hardware-in-the-loop test. Fig. 14 shows the results for the vehicle acceleration variation. It can be seen from Figs. 13 and 14 that the experimental and simulation results for the vehicle yaw rate and the vehicle lateral acceleration show very close agreement.

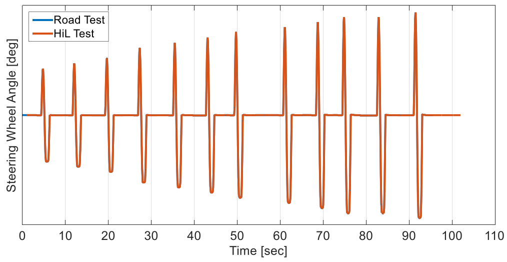


Fig. 11 The steering input for FMVSS No. 126 test

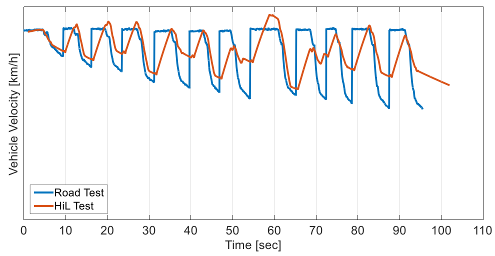


Fig. 12 Change of vehicle velocity over time for FMVSS No. 126

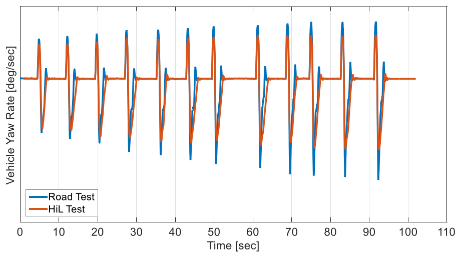


Fig. 13 Change of vehicle yaw rate over time for FMVSS No. 126

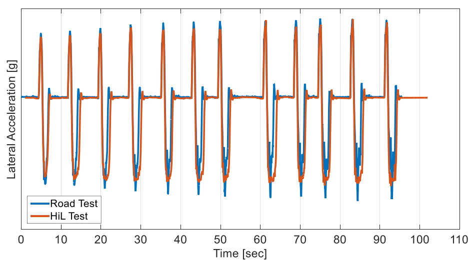


Fig. 14 Change of vehicle lateral acceleration over time for FMVSS No. 126

Fig. 15 shows the moments which the ESC runs for the road test and hardware-in-the-loop test. Good coherence is achieved for the ESC switching points. The overall working time is similar. However, the actual vehicle ESC made more switching than the simulator at some points.

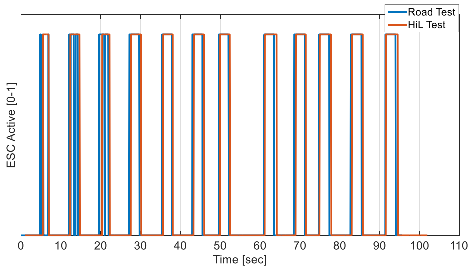


Fig. 15 ESC switching points for FMVSS No. 126

According to the results, FMVSS No. 126 test running in the hardware-in-the-loop simulator was in compliance with the actual road test results. Hereafter, the development of the ESC evaluation criterion is described.

### *4.2 ESC evaluation score*

ESC acceptance and evaluation criterion consist of two stages. The comparable performance of the ESC algorithms can be determined by subjecting the vehicle controllers, which passed ESC acceptance criterion (FMVSS No. 126 test), to the ESC evaluation criterion. Fig. 16 shows the flow chart for the ESC acceptance and evaluation criterion. Evaluation can be done numerically by the proposed ESC evaluation score. The ESC evaluation score consists of error based and control performance based sub-sections.

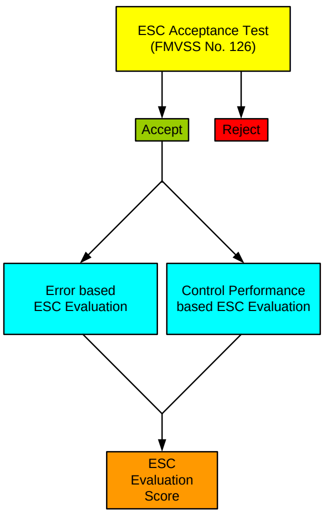


Fig. 16 The flow chart for ESC acceptance and evaluation criterion

### *4.2.1 Error based ESC evaluation score*

A numeric evaluation criterion for the comparison of the ESC algorithms, which passed FMVSS No. 126 test, is not available in the literature. In this paper, two different ESC evaluation criteria have been formulated to compare ESC algorithms from different perspectives. First of them is the error-based ESC evaluation criterion. The main purpose of the ESC systems is to maintain the vehicle lateral stability by keeping the vehicle yaw rate ($r$) and the vehicle side slip angle ($\beta$) around the desired values ($r_d$ and $\beta_d$). These two parameters, which are crucial to the stability of the vehicle lateral dynamics, have been used in determining the error-based ESC evaluation criterion.

After the tests are performed with the ESC controllers and the values are collected, the normalized mean root square error (NMRSE) values can be calculated by using the formula below for the vehicle yaw rate and the vehicle side slip angle

$$NRMSE = \frac{\sqrt{\dfrac{\sum_{i=1}^{n}\left(\mathrm{x}_{measured}(\mathrm{i})\text{-}\mathrm{x}_{desired}(\mathrm{i})\right)^2}{n}}}{x_{\mathrm{desired,max}} - x_{\mathrm{desired,min}}} \tag{1}$$

where n is the number of data points used in the evaluation. x denotes the vehicle yaw rate or the vehicle side slip angle.

In this paper, two different ESC designs were used for comparison purposes. These designs are called the Basic ESC and the Integrated ESC. The Basic ESC is a PID based differential braking based lateral stability control system shown in Fig. 17. It consists of upper and lower controller parts. The upper controller part contains supervisor and PID based corrective yaw moment calculation part. The lower controller part includes braking pressure distribution algorithm. The desired yaw rate value ($r_d$) is compared with the measured value ($r$) and the yaw rate error value ($e_r$) is obtained in the supervisor block. The supervisor contains threshold value triggers in order to prevent the working of ESC system unnecessarily. Using this error value, the corrective yaw moment is obtained based on PID controller. This corrective moment is converted tire braking pressures and the decision of which tires will brake is made in the braking pressure distribution algorithm block. According to the sign of the control signal, left or right side tires brake.

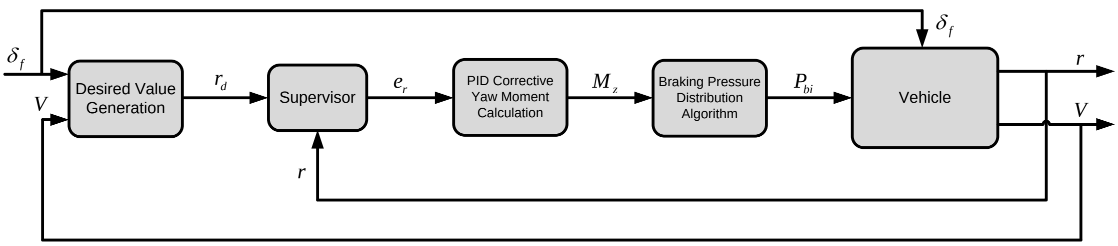


Fig. 17 The Basic ESC system block diagram

The Integrated ESC system contains subsystems such as desired value generation, supervisor, corrective yaw moment calculation, desired slip ratio calculation, slip ratio calculation, braking torque distribution algorithm, master cylinder pressure regulation and wheel slip controller. Unlike the Basic ESC system, in the Integrated ESC system both vehicle side slip angle and yaw rate are feedbacked. The corrective yaw moment calculation is performed using a scheduled LQR controller and it is applied to the vehicle by individual braking. The braking torque distribution algorithm and wheel slip control system are utilized as lower controllers. The wheel slip controller includes bang-bang controller and hydraulic brake actuator model to obtain tire braking pressures ($P_{bi}$). The details of the Integrated ESC system can be found in (Emirler *et al.* 2015).

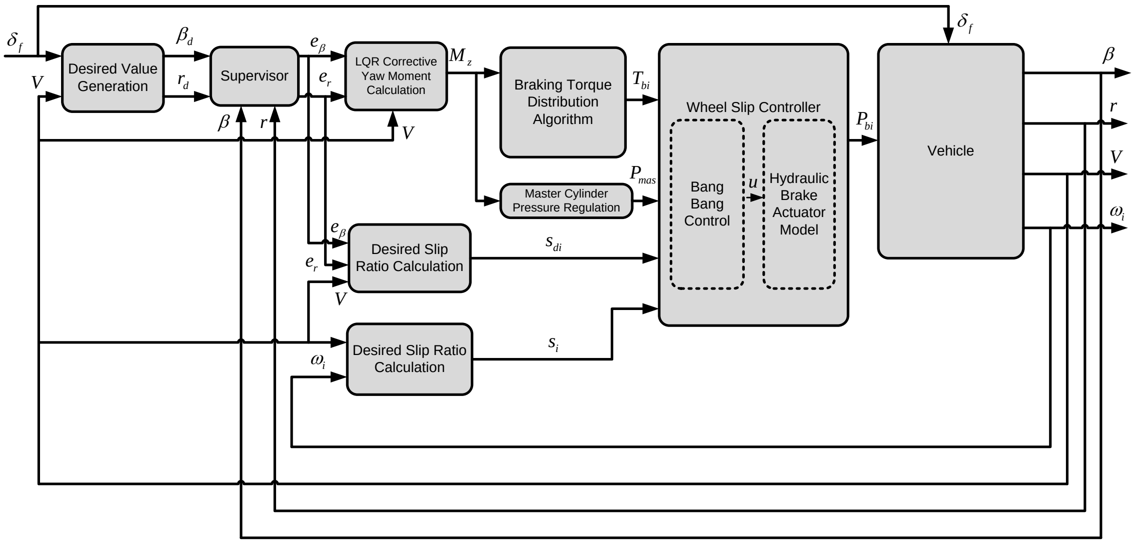


Fig. 18 The Integrated ESC system block diagram

Simulations were carried out for three different road tests (Fishhook, Sine-with-dwell and standard FMVSS No. 126) in the CarSim environment. For the cases of uncontrolled vehicle, the Basic ESC equipped vehicle and the Integrated ESC equipped vehicle, NRMSE results were obtained. Note that a single sine wave is used in Sine-with-dwell test as the steering input. On the other hand, a repetitive and increasing sine wave is used as the steering input in FMVSS No. 126 test, as detailed in the previous section.

Table 1 shows the error values of uncontrolled, the Basic ESC equipped and the Integrated ESC equipped vehicles in Fishhook test.

Table 1 Error values calculated for Fishhook test

| | Fishhook Test | |
|---|---|---|
| | Yaw rate NMRSE value | Side slip angle NMRSE value |
| Uncontrolled | 0.0159 | 0.3471 |
| Basic ESC | 0.0042 | 0.1974 |
| Integrated ESC | 0.0085 | 0.1748 |

Table 2 shows the error values of uncontrolled, the Basic ESC equipped and the Integrated ESC equipped vehicles in Sine-with-dwell test.

Table 2 Error values calculated for Sine-with-dwell test

| | Sine-with-dwell Test | |
|---|---|---|
| | Yaw rate NMRSE value | Side slip angle NMRSE value |
| Uncontrolled | 0.0099 | 0.0410 |
| Basic ESC | 0.0012 | 0.0203 |
| Integrated ESC | 0.0053 | 0.0237 |

Table 3 shows the error values of uncontrolled, the Basic ESC equipped and the Integrated ESC equipped vehicles in FMVSS No. 126 test.

Table 3 Error values calculated for FMVSS No. 126 test

| | FMVSS No. 126 Test | |
|---|---|---|
| | Yaw rate NMRSE value | Side slip angle NMRSE value |
| Uncontrolled | 0.0147 | 0.0780 |
| Basic ESC | 0.0057 | 0.0353 |
| Integrated ESC | 0.0035 | 0.0334 |

Table 4 E-ESC-ES values calculated for different tests (w = 0.5)

| | E-ESC-ES (0-100) | |
|---|---|---|
| | Basic ESC | Integrated ESC |
| Fishhook | 59.6875 | 63.3447 |
| Sine-with-dwell | 95.6963 | 94.2121 |
| FMVSS No. 126 | 59.0446 | 63.1238 |

The following formula has been proposed for the error-based ESC evaluation score calculation

$$\text{E-ESC-ES} = 100 - \left( we_r + (1-w)e_\beta \right) PF \tag{2}$$

where E-ESC-ES is the error-based ESC evaluation score, $e_r$ is NMRSE of vehicle yaw rate, $e_\beta$ is NMRSE of vehicle side slip angle. $w$ is a weight value that can be selected from 0 to 1. By changing this value, it is possible to bias the ESC evaluation score more towards vehicle yaw rate error or vehicle side slip angle error. $PF$ is the percentage factor used to set the calculated evaluation score as a percentage.

E-ESC-ES is a number between 0 and 100. Theoretically, if the error values are zero, the tested ESC takes 100 points. The vehicle, which shows better behavior (less skidding and less lateral slip), get a higher score. The E-ESC-ES values calculated for different tests are given in Table 4. The weight value, $w$, was taken as 0.5 in the calculations. Thus, equal weight was given to the vehicle yaw rate and the vehicle side slip error.

Fig. 19 shows the Basic ESC and the Integrated ESC evaluation scores for Fishhook test with different weights. When the weight $w$ is 0, only the vehicle side slip error value is taken into account according to Eq. (2). Similarly, if the weight $w$ is 1, then only the vehicle yaw rate is considered in the calculations. In the intermediate weight values, the participation rate of errors varies. It can be seen from Fig. 19 that Integrated ESC for Fishhook maneuver generally takes higher scores than the Basic ESC. As the effect of the vehicle yaw rate error value is increased, the score difference between the two controllers is reduced. If the evaluation is made only according to the vehicle yaw rate, the Basic ESC can get a bigger score even if there is a slight difference. Such a weighted calculation method allows the user to evaluate the ESCs from a broader perspective.

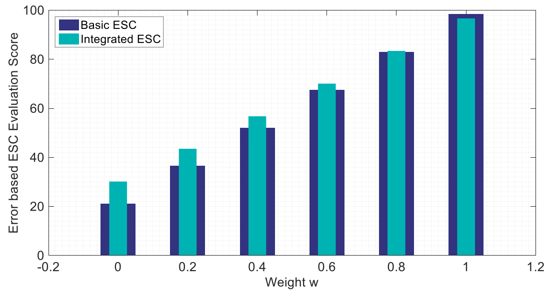


Fig. 19 Error based ESC evaluation scores for Fishhook test using different weights

Fig. 20 shows ESC evaluation scores of the Basic and the Integrated ESCs for Sine-with-dwell test using different weights. It can be seen that the scores of ESCs for all weight values are very close to each other. The Basic ESC for this maneuver seems to be slightly more successful than the Integrated ESC.

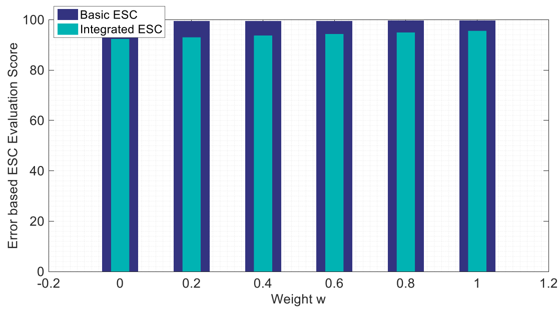


Fig. 20 Error based ESC evaluation scores for Sine-with-Dwell test using different weights

Fig. 21 shows ESC evaluation scores of the Basic and the Integrated ESCs for FMVSS No. 126 test using different weights. It can be seen that the scores of the Integrated ESC for all weight values is higher than the Basic ESC. The Integrated ESC for this maneuver is more successful.

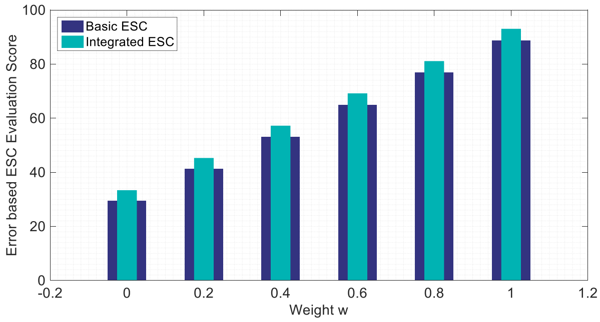


Fig. 21 Error based ESC evaluation scores for FMVSS No. 126 test using different weights

When all the results from all the tests are evaluated together, it is seen that the Integrated ESC gives slightly better results (less skidding and less lateral slip) than the Basic ESC according to the error-based evaluation.

### *4.2.2 Control performance-based ESC evaluation score*

In addition to error-based ESC evaluation, an evaluation criterion can also be determined by examining the transient response of the controlled vehicle. This criterion is named control performance-based ESC evaluation score. A test maneuver was created to compare the vehicle yaw rate time responses. In this maneuver, the vehicle is driven at a steady speed of 80 km/h while the steering wheel is turned by 120 degrees in 1 second. The tire-road friction coefficient was taken as 0.85 to consider realistic road conditions. Both the Basic ESC and the Integrated ESC were subjected to this test and the evaluation score based on the control performance was obtained for both control systems.

Step response characteristics such as rise time (RT), settling time (ST), overshoot percentage (OS) and peak value (PK) can be used when a time response dependent evaluation criterion is desired to be developed. The rise time is defined as the time to reach from the 10% response to the 90% response. The settling time is defined as the time to reach 98% of the response. The percentage overshoot is the ratio of the difference between the peak value and the steady state value to the steady state value of the system response. Peak value is the maximum absolute value that the system response can reach. Fig. 22 shows the step response characteristics.

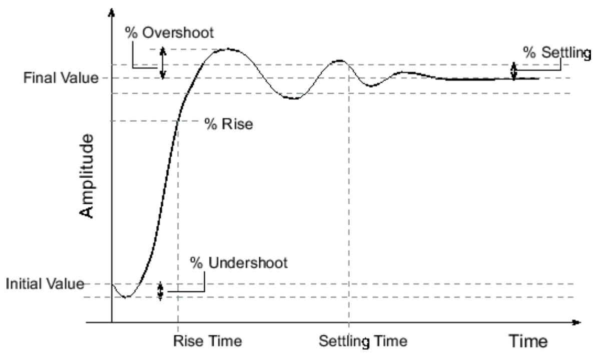


Fig. 22 Step response characteristics (Mathworks 2016)

The following formula is proposed for the control performance-based ESC evaluation score calculations

$$\text{C-ESC-ES} = 100 - \left( w_{RT} RT + w_{ST} ST + w_{OS} OS + w_{PK} PK \right) PF \tag{3}$$

where C-ESC-ES is the control performance-based ESC evaluation score, *RT* is the rise time, *ST* is the settling time, *OS* is the percentage overshoot and PK is the peak value. $w_{RT}$, $w_{ST}$, $w_{OS}$ and $w_{PK}$ denote the weights related to the rise time, the settling time, the percentage overshoot and the peak value, respectively. The summation of these weights is equal to 1. By changing these weight values, it is possible to alter the effect of control performance characteristics on the calculation of ESC evaluation score. For example, if the settling time comparison of the ESC systems is important, the weight of the settling time ($w_{ST}$) can be selected to be higher than the other weights. As another example, if only rise time of the ESC systems is desired to be compared, the weight of rise time can be selected as 1 and the other weights can be taken as 0. *PF* is the percentage factor used to set the calculated evaluation score as a percentage. Here, *PF* is taken as 10 as an example.

According to the defined maneuver, the vehicle yaw rate responses of the Basic ESC and the Integrated ESC equipped vehicles are shown in Fig. 23. Also, Fig. 24 shows the switching points of the ESC algorithms. The different characteristics of the Basic ESC and the Integrated ESC equipped vehicles can be seen from these figures.

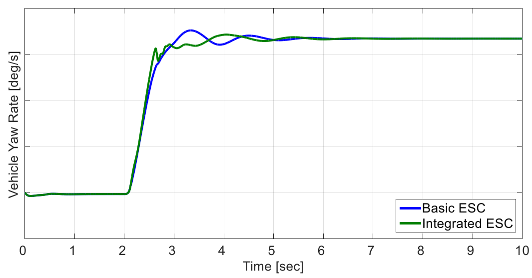


Fig. 23 Vehicle yaw rate results for Basic and Integrated ESCs

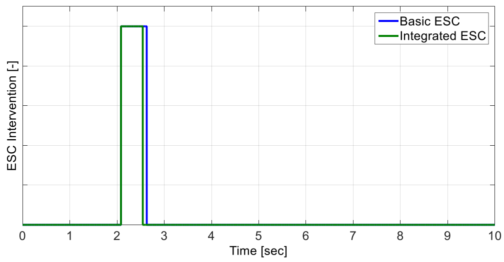


Fig. 24 ESC switching points for Basic and Integrated ESCs

Table 5 shows the values of the step response characteristics calculated in both tests.

The control performance-based ESC evaluation, which can be calculated by Eq. (3), is given in Table 6 for the Basic ESC and the Integrated ESC cases. It is seen that the ESC evaluation score of the Integrated ESC is higher than the Basic ESC.

Table 5 The values of the step response characteristics for the Basic and the Integrated ESC equipped vehicles

| | Basic ESC | Integrated ESC |
|---|---|---|
| Rise Time (RT) (sec) | 0.6278 | 0.4426 |
| Settling Time (ST) (sec) | 4.1150 | 4.2126 |
| Percentage Overshoot (%) | 5.3302 | 2.6217 |
| Peak Value (PK) (rad/sec) | 0.3520 | 0.3429 |

Table 6 Control performance-based ESC evaluation scores for the Basic ESC and the Integrated ESC

| | C-ESC-ES |
|---|---|
| Basic ESC | 73.9375 |
| Integrated ESC | 80.9504 |

### *4.2.3 Calculation of ESC evaluation score*

The ESC evaluation score can be obtained by combining evaluation scores based on error and control performance. The final score can be calculated using the following formula

$$\text{ESC-ES} = \left( w_{ES}\,\text{E-ESC-ES} + \left(1 - w_{ES}\right)\text{C-ESC-ES}\right) \tag{4}$$

where ESC-ES shows the final evaluation score. Score type weighting is done with the weight, $w_{ES}$. The evaluation scores calculated for various tests are given in Table 7.

Table 7 ESC evaluation scores for various tests ($w_{ES}$ = 0.5)

| | ESC-ES (0-100) | |
|---|---|---|
| | Basic ESC | Integrated ESC |
| Fishhook | 66.8125 | 72.1475 |
| Sine-with-dwell | 84.8169 | 87.5813 |
| FMVSS No. 126 | 66.4911 | 72.0371 |
| Average of tests | 72.7068 | 77.2553 |

According to the numerical results in Table 7, the two ESC algorithms can be compared with each other. The number of tests can be increased for different maneuvers and the results can be examined. Two ESCs can be evaluated with a single score by taking the average of the results obtained from the different tests. In the last row of Table 7, the average of ESC scores obtained from three different tests are shown. It is seen that more successful results are be obtained using the Integrated ESC as compared to the Basic ESC.

## 5. Conclusions

In this paper, a real time CarSim vehicle model has been introduced and a validation study has been conducted according to the actual test data. The parameters of the vehicle model were fine-tuned to capture the actual vehicle behavior. This validated model was employed in the Tofaş R&D hardware-in-the-loop vehicle simulator. The hardware-in-the-loop simulations were carried out by the help of this simulator. For example, the FMVSS No. 126 standard ESC test was performed in and the results were compared to experimental results. It has been seen that the simulation results closely fit the experimental results. For the comparison of different ESC algorithms, several evaluation criteria were proposed such as error based and control performance-based evaluation scores. According to these scores, the integrated ESC algorithm gave better results than the Basic ESC algorithm. As part of future work, similar evaluation studies will be performed for adaptive cruise control and cooperative adaptive cruise control systems.

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## Note

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## References

*CarSim Applications: The Sine with Dwell Test Manual* (2011).

Emirler, M.T., Kahraman, K., Şentürk, M., Acar, O.U., Aksun Güvenç, B., Güvenç, L. and Efendioğlu, B. (2015), "Lateral stability control of fully electric vehicles", *Int. J. Automot. Technol.*, **16**(2), 317-328.

Emirler, M.T., Uygan, İ.M.C., Gelbal, Ş.Y., Gözü, M., Böke, T.A., Aksun Güvenç, B. and Güvenç, L. (2014), "Vehicle dynamics modeling and validation for a hardware-in-the-loop vehicle simulator", *Proceedings of the 7th Automotive Technologies Congress*, Bursa, Turkey, May.

Emirler, M.T., Uygan, İ.M.C., Gelbal, Ş.Y., Gözü, M., Böke, T.A., Aksun Güvenç, B. and Güvenç, L. (2016), "Vehicle dynamics modeling and validation for hardware-in-the-loop testing of electronic stability control", *Int. J. Vehic. Des.*, **71**(1-4), 191-211.

Gietelink, O., Ploeg, J., De Schutter, B. and Verhaegen, M. (2006), "Development of advanced driver assistance sytems with vehicle hardware-in-the-loop simulations", *Vehic. Syst. Dyn.*, **44**(7), 569-590.

Heidrich, L., Shyrokau, B., Savitski, D., Ivanov, V., Augsburg, K. and Wang, D. (2013), "Hardware-in-the-loop test rig for integrated vehicle control systems", *Proceedings of the 7th IFAC Symposium on Advances in Automotive Control*, Tokyo, Japan, September.

Kahraman, K., Şentürk, M., Emirler, M.T., Bozkurt, E., Aksun Güvenç, B., Güvenç, L. and Efendioğlu, B., (2012), "Offline and hardware-in-the-loop simulation model/system development for electronic stability control of a fully electric vehicle", *Proceedings of the 6th Automotive Technologies Congress*, Bursa, Turkey, June.

Mathworks (2016), <https://www.mathworks.com/help/sldo/ug/specify-design-requirements-gui.html>.

NHTSA (2007), *FMVSS No. 126 Electronic Stability Control Systems*, U.S. Department of Transportation.

Peperhowe, M., Haupt, H., Liem, K. and Schindler, W. (2013), "Efficient testing of controller influenced vehicle dynamics", *Proceedings of the 7th IFAC Symposium on Advances in Automotive Control*, Tokyo, Japan, September.

Schuette, H. and Waeltermann, P. (2005), *Hardware-in-the-Loop Testing of Vehicle Dynamics Controllers-A Technical Survey*, SAE Technical Paper, No. 2005-01-1660.

Soltani, A. and Assadian, F. (2016), "A hardware-in-the-loop facility for integrated vehicle dynamics control system design and validation", *Proceedings of the 7th IFAC Symposium on Mechatronic Systems*, Leicestershire, U.K., September.

Sorniotti, A. (2004), *Hardware-in-the-Loop for Braking Systems with Anti-Lock Braking System and Electronic Stability Program*, SAE Technical Paper, No. 2004-01-2062.

Stahl, K. and Leimbach, K.D. (2014), "Vehicle dynamics simulation by using hardware-in-the-loop techniques", *Proceedings of the IEEE 17th International Conference on Intelligent Transportation Systems*, Qingdao, China, October.

UNECE (2009), *United Nations Economic Commission for Europe, Vehicle Regulations No:13-H Revision 1- Amendment 2*.

Velardocchia, M. and Sorniotti, A. (2005), *Hardware-in-the-Loop to Evaluate Active Braking Systems Performance*, SAE Technical Paper, No. 2005-01-1580.

Zheng, S., Tang, H., Han, Z. and Zhang, Y. (2006), "Controller design for vehicle stability enhancement", *Contr. Eng. Pract.*, **14**(12), 1413-1421.

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