Determination of sensitivity of the Electronic Stability Program Algorithm

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The main aim of this research is determination of ESP algorithm sensitivity. In order to determine the algorithm's sensitivity a test on a car was conducted. During the test measurements of car velocity, yaw rate and lateral acceleration were done and further compared with theoretical values. This allowed to indicate the sensitive zone of the ESP system in the car.

Keywords: ESP, sensitivity of ESP, ESP algorithm, yaw rate, lateral acceleration.

1. Introduction

In spite of the fact that ESP system is present in every modern car, it is difficult to find specific technical data about the algorithm. This is due to the fact that it is black-boxed and most of the data is confidential.

ESP consists of microcomputer which monitors signals from sensors and compare intended (theoretical) and actual car trajectory. Most of ESP systems measures individual speed of each wheel, yaw rate that is rotation of the car about horizontal axis in degrees per second, lateral acceleration and driver input (steering angle and car velocity). If the trajectories differ from each other, ESP uses the vehicle's braking system selectively braking each wheel, or reduces engine torque, to stabilize the vehicle [1]. However, the ESP configurations may differ between different cars. The ESP software can be programmed in a way that allows for a certain deviation

from intended trajectory, whereas others react immediately before the driver can
even notice the loss of traction [2].

The ESP sensitivity can be checked basing on measurement of the lateral acceler-
ation, yaw rate and car speed. The angle of wheels rotation should be known and
constant during measurement. In this way, having car velocity and wheels rotation,
theoretical yaw rate can be calculated and compared with the measured value. The
difference between theoretical and actual yaw rate, as well as lateral acceleration, at
the moment of ESP activation is a control parameter of the system sensitivity [3].
The main aim of this research is to investigate the ESP sensitivity in a car. In
the remaining sections of the article, principles of working of the ESP system are
explained. Then, the procedure of performing experiment, obtaining and analyzing
data is described. Next, results and observations made during the experiment are
shown. Data interpretation and Conclusions are discussed in the last section.

1.1.   *Electronic Stability Program (ESP)*

As mentioned, ESP system detects and reduce loss of traction, thus improves vehicle
stability. When the actual yaw rate is greater than theoretical yaw rate, the car
behavior is described as oversteering behavior (skidding of the rear axle). In such
case, the ESP may brake the outer front wheel to generate counteracting force
moment. In case of understeering behavior, when the actual yaw rate is smaller than
theoretical one (the skidding of the front axle), the inner back wheel is braked [4].
The difference between theoretical and actual yaw rate is one of the main indicators
for ESP system. The difference is presented in equation below:

$$\Delta \Psi = \Psi - \Psi_t \tag{1}$$

where: Ψ – actual yaw rate, Ψ_t – theoretical yaw rate.

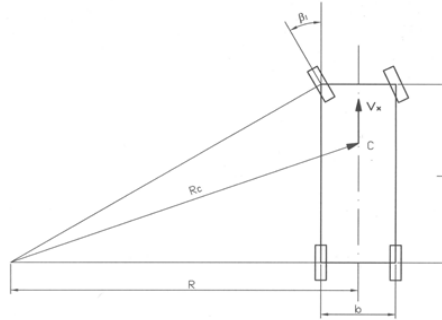**Figure 1** Theoretical yaw rate [3]

When $\Delta \Psi < 0$ the car understeer (car rotates not enough). $\Delta \Psi > 0$ oversteer (the
car rotates too much [5]).

$$\Psi_t = \frac{2V_x \tan \beta_1}{2L + b \tan \beta_1} \tag{2}$$

where: V_x – vehicle longitudal speed, $|beta_1$ – steering angle of the inner wheel, L – wheelbase of the vehicle, b – wheelbase (Fig. 1) [5].

Theoretical yaw rate value (2) is a yaw rate, that a vehicle in motion would have, if it traveled on the arc of a road with constant radius determined by the steering wheel angle without taking into the account, the phenomena of tire wear, and loss of transverse stability occurring during circular motion.

Another parameter which might be monitored by the system is difference between theoretical and actual lateral acceleration. If the difference is too high, the ESP system intervenes. The lateral acceleration difference is as follows:

$$\Delta a_y = a_y - a_{yt} \tag{3}$$

where: a_y – actual lateral acceleration, $a_{yt} = v^2/R_c$ – theoretical lateral acceleration, $R_c = L/\delta$ – radius of rotation from the centre of mass, $\delta = \beta_1 + \beta_2/2$ – average wheel turn angle, v, r – car velocity and radius of trajectory respectively [5].

ESP system usually allows for a small deviation of the car trajectory before intervention. The higher sensitivity, the smaller possible deviation is. Sensitivity of the ESP system is the value of Δa_y and $\Delta \Psi$ at which the ESP system activates to align the car actual trajectory with the intended trajectory evaluated basing on the drivers input. When Δa_y and $\Delta \Psi$ are small, it means that the car's actual trajectory does not differ much from the one intended by the driver.

1.2. *ESP algorithm*

Exact technology of ESP is kept in secret by car producers. In this chapter the most probable flowchart of ESP algorithm is described (see Fig. 2). A flowchart of ESP control system consists of 4 blocks: input block, calculation block, decision block and executive block. After decision block, if there is no intervention of the system, the process starts again [5].

Input block is responsible for measurements of parameters of car dynamics. Such as:

- Steering angle of steering wheel – α_k

- Angular velocities of individual wheels of the vehicle N1 ... N4

- Yaw rate – $\dot{\Psi}$

- Lateral acceleration of the vehicle – a_y

Calculation block calculates the physical quantities related to the movement of the vehicle, where the real-time measurement is not carried out, or execution of such a measure for technical reasons, would not be possible. All measurements are made on the basis of the measured values of physical quantities and based on the data of the vehicle structure. The main task of the block calculation is to determine the values of the three basic parameters of motion:
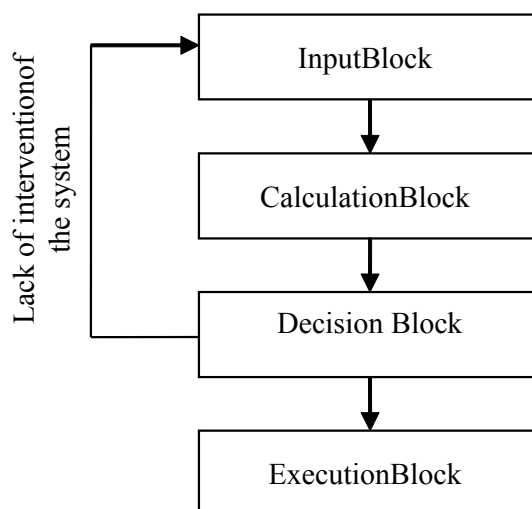
- longitudinal speed of the vehicle – V_x

Figure 2 Algorithm of ESP [5]

- theoretical yaw rate – $\dot{\Psi}$

- theoretical lateral acceleration – a_{yt}

Decision block on the basis of the measurement data and the calculated theoretical yaw rate as well as the theoretical lateral acceleration a_{yt}, at first decides on the intervention of the ESP. Yaw rate as well as lateral acceleration have a degree of tolerance that sets the sensitive zone of the device. The sensitivity of the system corresponds to the quality of operation and ESP is selected on the basis of experimental studies, because it largely depends on the design of the controlled vehicle. The system makes decisions about intervention when the at least one of the two parameters exceeds the limits of tolerance. In the second phase, the task of decision block is the detection of the situation, which led to the loss of stability of the vehicle.

Executive block is responsible for developing logic signal, which will allows ESP system to control the movement of the vehicle by means of breaking system or by reduction of driving torque [3].

1.3. *Problem definition*

The aim was to determine the range of sensitivity of the ESP algorithm. The sensitivity of the system corresponds to the quality of operation. Yaw rate as well as lateral acceleration have a degree of tolerance that sets the sensitive zone of the device. Therefore actual yaw rate and lateral acceleration are measured. Then, theoretical values of those parameters are evaluated. Having both, actual and theoretical values, the ESP sensitivity may be determined.

1.4.   *State Of The Art*

Modern road cars are highly developeddeveloped, and it is common to believe that little improvement in cars' performance can be done by passive means. Nowadays, the performance is improved by means of active systems which complement the passive behavior of the vehicle [1]. There is plenty of research conducted about both passive ways and active systems improving car's behavior. Many of them describe tire behavior, suspension systems or driver abilities [2, 3, 4, 5], while other focuses on active systems [6]. However, even though there is many researches done concerning electronic stability program [5, 7, 9, 10], none of them indicates the sensitivity range of ESP. Scientists focus on providing general model, that could be used for computer simulations of ESP performance [11, 12]. There exist road tests and ESP performance examinations done as individual studies by automotive companies [12]. Commercial ESC systems have black-boxed proprietary algorithms and the controllers are fine-tuned for a particular vehicle model. This confidentiality ensures future profits for individual companies, while at the same time creating problems for lawyers' mechanics and forensic experts, investigating car accidents, and ensuring commonality while creating laws concerning standard safety regulations for road vehicles. Measuring the sensitivity requires a large amount of vehicle performance data under different maneuvers and road conditions. While different studies concerning ESP Systems, its dynamics and computer simulations of its actions, the field still lacks a concise study of quality and sensitivity of ESP Systems in action. This paper tries to fill that gap in common knowledge. Closest approximate was the work of van Putten, who aimed to investigate an ESP system in detail to obtain an efficient and effective ESP system model, which is then built in a Matlab/Simulink environment to suit veDYNA vehicle simulation software. An analytical analysis, supported by experimental results, shows the abilities of an ESP, using sensitivities to determine at which wheel an intervention takes place and a combination of the direct influence of braking as well as its secondary effect, to control vehicle behaviour under critical circumstances. [23] Unfortunately simulated tests were conducted only during drive forward, and as such were of no use in our research focused on circular path of movement.

2.   Experimental procedure

The experiment of measuring ESP sensitivity is not trivial, special preparations before performing the measurements are required. During experiment Seat Toledo III was tested. Sensors were placed in the centrecenter of gravity, during experiment following parameters were measured:

- lateral acceleration with Crossbow IMU-300CC,

- yaw rate of the vehicle with Crossbow IMU-300CC,

- the angle of front wheels, which corresponds to indented trajectory, with turntable,

- linear speed of the car with DATRON Messtechnik Correvit LM - 066/12.

2.1. *Measuring equipment*

Measuring equipment has been connected according to the diagram below (Fig.3).
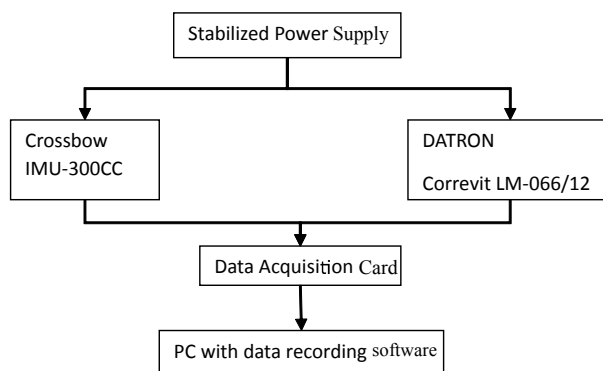

Figure 3 Sensor connection schematic

Both sensors (Inertial Measuring Unit and Velocity Sensor) were connected to the data acquisition card, through which data was concentrated and transferred to a PC with DAQView data acquisition software. In this software parameters were set translating raw data values in volts into correct units.

Correvit Velocity Sensor was calibrated according to data obtained from Correvit calibration sheet, in which velocity translation value is 40 (40 km/h per 1V).

According to Crossbow Inertial Measuring Unit instruction calibration is not necessary, translation values differ in every position of the axis (-1G, 0G, +1G).

The Crossbow IMU300CC is an intelligent six degree-of-freedom (6DOF) Inertial System designed for general measurement of linear acceleration and angular rate in dynamic environments.

The IMU300CC uses a high performance Digital Signal Processor to provide outputs that are compensated for deterministic error sources within the unit. Internal compensation includes offset, scale factor and alignment.

Correvit optical sensors enable direct, slip-free measurement of longitudinal velocity in vehicle driving dynamics tests. They use the proven Correvit technology (optical transducer) for non-contact measurement of speed. The sensor consists of optical tube with integrated signal amplifier and amplitude control fixed with the illumination part. It Functions on the basis of optical correlator according to the spatial frequency filter process. Output from the sensor consists of a raw signal in volts.

Data acquisition is the process of sampling signals that measure real world physical conditions and converting the resulting samples into digital numeric values that can be manipulated by a computer. Data acquisition systems, abbreviated by the acronyms DAS or DAQ, typically convert analog waveforms into digital values for processing. The components of data acquisition systems include:

- Sensors, to convert physical parameters to electrical signals.

- Signal conditioning circuitry, to convert sensor signals into a form that can be converted to digital values.

- Analog-to-digital converters, to convert conditioned sensor signals to digital values.

The Personal Daq/3000 Series devices provide high-speed, multifunction USB data acquisition (DAQ). Features include analog voltage or thermocouple input per channel along with digital I/O and counter functions with quadrature encoder support and up to four analog outputs.
Power supply is a standard laboratory stabilized DC power supply with current control.

2.2. *Experiment*

Preparation to measurements of lateral acceleration, yaw rate and car velocity includes several steps. Determination of mass centrecenter of gravity is the first step. Secondly, parameters are set for the Inertial Measuring Unit. The third step includes mounting of all measuring devices on the car. The blocking of steering wheel is the fourth step.
In order to place the measuring devices properly, mass centrecenter of gravity of tested car should be determined. To determine the position of center of gravity car was weighted. A pair of special scales (see Fig. 4) was placed under the front axis of the car.
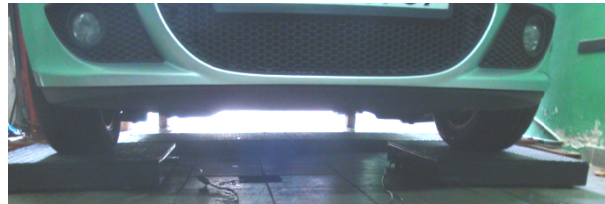

Figure 4 Measurement of the front wheels load

To determine the position of the centrecenter between front and rear axis, in Fig. 5 denoted as distance a, the car was weighed on a flat surface. Readings from weights were multiplied by gravity acceleration to obtain loads. To calculate the distance a, flowing formula was used:

$$M_T = M_R + M_F \tag{4}$$

$$a = L\frac{M_R}{M_T} \tag{5}$$

where: M_T – total load of car, M_R – load on rear axis, M_F – load o front axis, L – distance between axis.
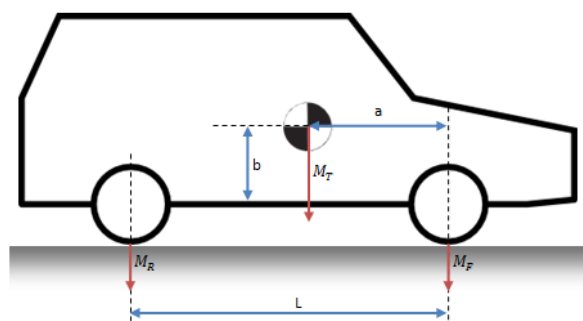
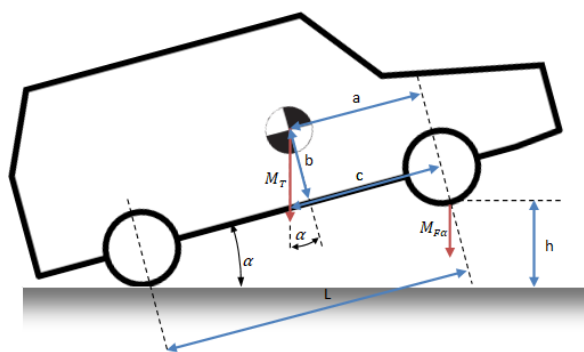**Figure 5** Determination of car's centre of gravity

Figure 6 Determination of car's centre of gravity - car at inclination

To determine vertical position of the centrecenter of gravity (distance b) car was inclined at an angle α, (see Fig. 6), and scales were placed under the front wheels, as it is presented in Fig.7. Angle was measured using protractor. To calculate the distance a, flowing formula was used:

$$c = L\left(1 - \frac{M_{F\alpha}}{M_T}\right) \qquad (6)$$

$$b = \frac{c - a}{\tan \alpha} \qquad (7)$$

where $M_{F\alpha}$ – load on front axis inclined at an angle.

Tab. 1 presents data collected from technical cards of a car and preformed measurements and calculations.

Table 1 Weight data

Car	M_T [N]	M_R [N]	M_F [N]	$M_{F\alpha}$ [N]	L [m]	a [m]	b [m]	c [m]	α [°]
SeatToledo	15205.5	6965.1	8240.4	7946.1	2.58	1.15	0.21	1.19	11

Figure 7 Determination of center of gravity - Seat Toledo III

Figure 8 Experimental setup; Crossbow IMU-300CC - Seat Toledo III

Sensors were placed in the centrecenter of gravity of a car and connected to real time data acquisition card. Power supply was connected to car socket with a current converter.

Data from card were instantly transferred to the computer with DAQ software., which transform the signal in mV to m/s and m/s^2. To mount the Inertial Measurement Unit, special stand was constructed and adjusted in the car (see Fig. 8).

As the Velocity Sensor measures the velocity using optical signal it has to be mounted outside the tested car, as shown in Fig. 9. The device was attached to the passenger doors, the vertical position of centre of gravity was kept, however the distance from the horizontal was equal to r = 102 cm, these valuethese values was taken into account while analyzing the results.

Figure 9 Experimental setup; Correvit - Seat Toledo III

In order to adjust an angle of intended the front wheel, the car was placed on turntables and the steering wheel was turned (see Fig. 10). While tests driver was focused on keeping the constant angle of intended trajectory. The angle was measured as 28 degrees on inner wheel and 24.5 degrees for outer wheel.

Figure 10 Front wheel on turntable

The constant steering-angle test method was chosen according to ISO 4138:2002. In this method the steering angle is fixedfixed, and the path radius is calculated basing on measurements.

Measurements were carried out on surface made of paving. When all the sensors were mounted in proper position, the experiment was conducted. Driver was adjusting the velocity to obtain the situation in which ESP system switch on, which is the situation of loss of vehicle's stability. Angle of intended trajectory was kept

constant. During the tests data were collected and transferred to the computer. Additionally, the car signalizes the activation of ESP system by lighting the control on the dashboard. Those signals were recorded using camera to compare the time moments with the results. Firstly, measurements were performed while turning left (driving in anticlockwise direction). Then, measurements in the clockwise direction were performed. Two sets of measurements in each direction (four sets all together) were performed.

3. Results analysis and discussion

First of allFirst, it must be mentioned that raw measurements were post-processed and only data after post-processing are shown in this section. Brown's simple exponential smoothing was applied to all data. In case of acceleration in Z axis, noise reduction was additionally performed.

Brown's simple exponential smoothing is given by the formula [6]:

$$s_t = \begin{cases} x_t & \text{for} \quad t = 1 \\ \alpha x_t + (1 - \alpha)s_{t-1} & \text{for} \quad t > 1 \end{cases} \tag{8}$$

where s_t is the smoothed statistic, x_t – current observation, α – smoothing factor: $\alpha = 0.1$ for velocity approximation, $\alpha = 0.05$ for the rest of measured parameters. Smoothing factor was chosen according to recommendations in the literature [6, 7, 8]. As mentioned in the Introduction, theoretical values of lateral acceleration and yaw rate had to be calculated according to equations (2) and (3), in order to compare them with the measured value. Moreover, measured value of lateral acceleration and yaw rate was corrected by roll angle of the car. It was done on basis of measured values of Z acceleration. It is worth to mention, that the yaw rate is negative because of the setting of the Inertial Measuring Unit. Positive values of the acceleration in the Z direction are obtained when the vector of acceleration is directed downward. Therefore, the rotation about Z axis (yaw) is positive when the car rotates clockwise.
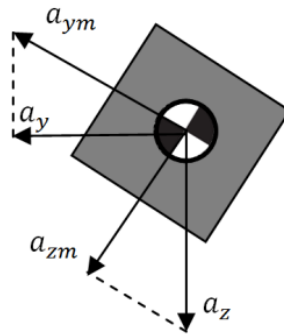

Figure 11 Actual and measured parameters

Measured and actual vectors of accelerations are presented in Fig. 11, where are actual values, and subscript m stands for "measured" value. It can be derived from simple geometrical dependencies, that value of is:

$$a_y = \frac{a_{ym}\, a_z}{a_z} \tag{9}$$

where: $a_z = 9.81$ m/s^2

Since the velocity sensor was placed at the side of the car, the value of the velocity also had to be corrected by the distance between car's centre of gravity and the sensor (denoted as in eq. 9).

$$V_x = \frac{V_{xm}(R_c \pm e)}{R_c} \tag{10}$$

Corrected values (9) and (10) of a_y and V_x are further compared with the theoretical ones. In this section only graphs of $\Delta\Psi$ and Δa_y are presented.

In Fig 12 below, results of the first measurement, turning in the left direction, are presented. A significant difference between actual and theoretical lateral acceleration around 26 sec. may be noticed. At that time moment, difference in the yaw rate increases as well. From this, it can be deduced, that the car was slightly oversteering before 26 sec. After 26 sec. the behaviour changed to understeering (value of theoretical parameters greater than actual). It may be concluded from this, that ESP activated around 28 sec. Observation from inside of the car confirms, that the first activation of the ESP took place around that time. Then, at 29 sec Δa_y decreases almost to zero. However, even though $\Delta\Psi$ decreases, it is still around 5 deg/s. Probably, just after that moment ESP system was turned off by the computer since the values of Δa_y and $\Delta\Psi$ where low enough. Just after that moment, there is immediate rise of the theoretical values. Again, the car behaviour became understeering. Interesting behaviour can be observed between 29 and 38 sec, the values fluctuate. It seems, that the computer tried to correct the trajectory by e.g. braking the inner wheel and thus, generating a moment rotating the car. Than the value increases, which may be caused be the blockage of the wheel or just by stop of the braking action. However, for all that time ESP probably was activated. Around 41 sec $\Delta\Psi$ and Δa_y again decreases nearly to 0. Small differences may be noticed after that. Next peek may be observed around 46 sec in case of Δa_y and at 47 sec in $\Delta\Psi$. After that time, the values decreases which may suggest activation of the ESP system.

It may be concluded that whenever the values of $\Delta\Psi$ and Δa_y achieve a peak – increases to a certain point and then decreases – the ESP system activates. In the results presented in Fig. 12, the critical values of Δa_y and $\Delta\Psi$ representing the system's sensitivity are about 1.25 m/s^2 and 12 rad/s respectively.

In Fig. 13 the results of subsequent measurement, while driving in the left direction, are presented. First increase in $\Delta\Psi$ and Δa_y may be noticed after 2 sec. About 18 sec. both values approach first peak ($\Delta\Psi = 5$ rad/s, $\Delta a_y = 1$) and then decrease to values about $\Delta\Psi$ 1 deg/s and Δa_y at 12 sec. This may suggest that the ESP activated at 18 sec. and corrected the trajectory of the car. Next significant increases takes place at 27 sec., 40 sec and 42 sec., which probably indicate the activation of the ESP at those time moments.

Results of both of two measurement driving in the right direction are presented in Fig. 14 and Fig. 15.

Selected values of $\Delta\Psi$ and Δa_y at the peaks are presented in Tab. 2 and Tab. 3.
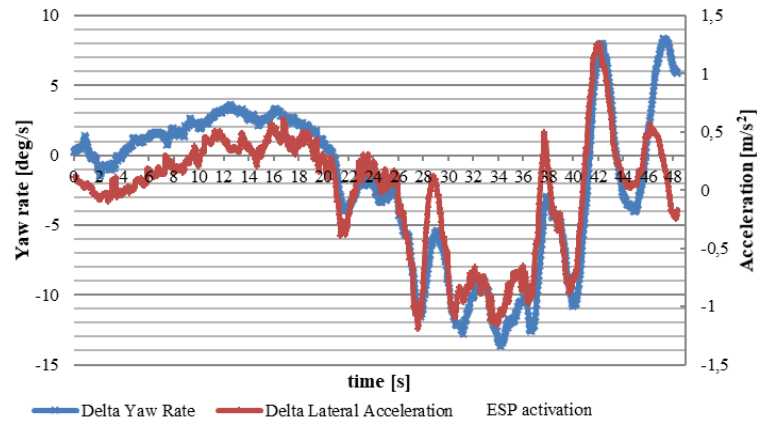

Figure 12 Difference between actual and theoretical values of parameters; left turn #1
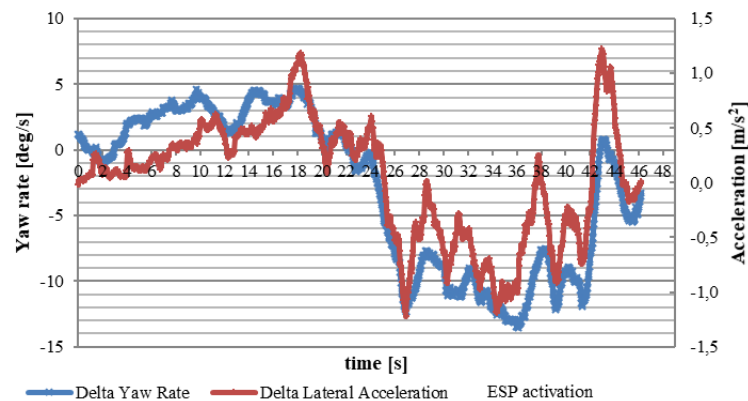

Figure 13 Difference between actual and theoretical values of parameters; left turn #2

As it can be observed, ESP activates when the absolute values of $\Delta\Psi$ and Δa_y are at least about 9 rad/s and 1 m/s^2 respectively. What is interesting, higher values of those parameters can be observed when the car was turning right, when the velocities where smaller. The probable reason is that the ESP sensitivity is dependent on the velocity. When a car has small velocity, it is highly probable that

driver correct the trajectory himself. The higher velocity is, the lower values of $\Delta\Psi$ and Δa_y are required to activate the system - the sensitivity is higher.
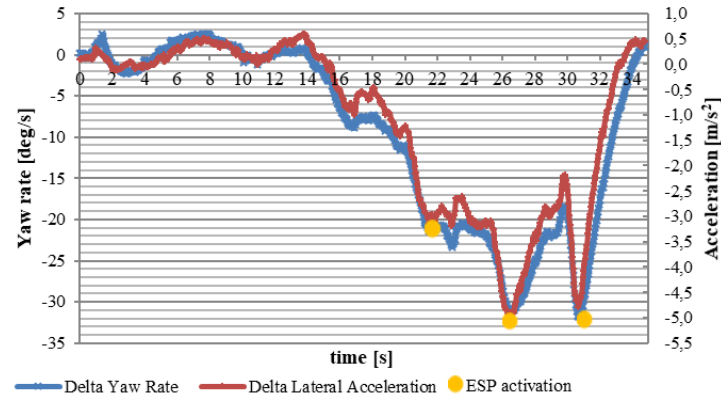

Figure 14 Difference between actual and theoretical values of parameters; right turn #1
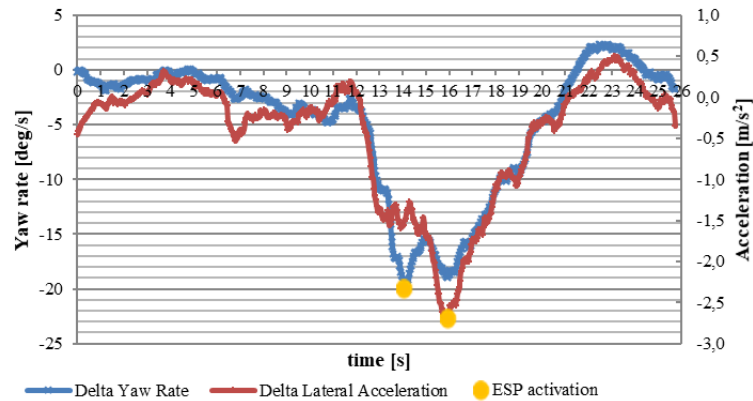

Figure 15 Difference between actual and theoretical values of parameters; right turn #2

Moreover, it should be mentioned, that noise was generated during the measurement. It was caused by a few factors. Firstly, Inertial Measuring Unit was mounted on long, aboutlong, about 0.5 m long, arm. It turned out the experimental stand was not rigid enough and the Inertial Measuring Unit was susceptible to small vibrations. The experiment was performed on parking lot with paving. Not regular surface could be the factor affecting the measurement with the velocity sensor which was used.

Table 2 Selected values of $\Delta\Psi$ and Δa_y at peaks, left turn

t [s]	$\Delta\Psi$ [deg/s]	Δa_y [m/s^2]
Left turn #1		
27.80	-11.57	-1.07
30.56	-12.15	-1.05
34.52	-11.74	-1.10
40.00	-10.85	-0.75
42.00	7.16	1.24
47.00	8.30	0.18
Left turn #2		
18.20	4.49	1.18
26.88	-12.34	-1.22
34.32	-12.31	-1.15
36.04	-13.39	-1.01
39.20	-12.15	-0.89
41.36	-11.90	-0.72
42.96	0.62	1.22

Table 3 Selected values of $\Delta\Psi$ and Δa_y at peaks, right turn

t [s]	$\Delta\Psi$ [deg/s]	Δa_y [m/s^2]
Right turn #1		
16.88	-8.88	-1.00
22.84	-22.88	-3.14
26.48	-31.24	-5.02
30.72	-31.85	-4.69
Right turn #2		
14.12	-19.95	-1.57
14.72	-16.19	-1.66
15.88	-18.85	-2.69

It can be pointed out that car rotates about x (longitudinal) axis during cornering. Since the Inertial Measuring Unit was fixed to the rig, value of actual yaw rate was influenced by the roll angle. Nevertheless, the roll angle in such case should not exceed 5°. ThereforeTherefore, the influence of it on yaw rate is negligible. Value of was recalculated and corrected by that angle, however the difference between measured and corrected value was not significant and could be omitted.

Small lag between theoretical and actual values may be due to different values of smoothing factors in the approximation. Both theoretical values were calculated basing on the velocity, which was approximated with $\alpha = 0.1$, while the rest of the parameters with . The higher the value of $\alpha = 0.05$, the lower value of the approximation lag with respect to real values, and the approximation is closer to the real values.

It can be noticed, that in some moments only one of parameters (Δa_y, $\Delta \Psi$) was high enough to trigger the activation of the ESP. Perhaps, $\Delta \Psi$ and Δa_y are not directly connected with each other. It is possible that ESP algorithm makes a decision on activation when at least one of the parameters exceeds the maximum allowable value.

4. Conclusions

As it was shown, the approximate critical values of $\Delta \Psi$ and Δa_y were established. Moreover, it was deduced that ESP sensitivity is dependent on car velocity, and is smaller when the velocity is smaller. Further research on this issue is recommended. Furthermore, it may be noticed that at some time moments ESP activated when the value of only one of parametersof parameters (Δa_y, $\Delta \Psi$) was greater than the critical value. It suggests that ESP algorithm activates when one or both of the parameters exceed its critical value.

The constant steering-angle test method was chosen according to ISO 4138:2002. As it is described, the steering angle was fixed and the path radius was calculated basing on measurements. However, due to the lack of measuring equipment, neither sideslip angle, nor steering wheel torque was measured. Moreover, minimum 20 meter path radius, recommended in the standard, could not be achieved due to lack urbanistic/logistic constraints. Continuous speed increase should be ensured.

Car speed in both clockwise and anticlockwise direction should be the same during experiments. It was not happened, which may be the cause that values of Δa_y and $\Delta \Psi$ obtained from measurements done during different tests differ from each other. Additionally, the only mostly peaks of Δa_y and $\Delta \Psi$ are marked on the graph. It should be emphasized, that peak signalizes only the moment of activation of ESP. After that, ESP is working in a way to correct the path of the vehicle and thus, reduce values of mentioned parameters.

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