Institutionen för systemteknik
Department of Electrical Engineering

Examensarbete

Implementation, validation and evaluation of an ESC system during a side impact using an advanced driving simulator

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan i Linköping
av

Anders Andersson

LITH-ISY-EX--09/4234--SE

Linköping 2009

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Titel
Title

Realisering, validering och utvärdering av ett antisladdsystem under en sidokrock i en avancerad bilsimulator

Implementation, validation and evaluation of an ESC system during a side impact using an advanced driving simulator

Författare
Author

Anders Andersson

Sammanfattning
Abstract

The objective of this thesis is to implement a basic, yet realistic, ESC system into the VTI simulator environment. This system is then validated to assure that it is working properly and provides a realistic behavior.

The implemented ESC system is used in a study, where the ESC system could be turned on and off, to evaluate the benefits of an ESC system after a side impact. This study shows that an ESC system may aid the driver in such a critical situation when the driver is unaware that a side impact will occur. With the ESC system active no driver lost control while with the system inactive there were five drivers that lost control, but deviations in initial speed give statistical difficulties, thus more tests are needed. In the case where the driver knows that an impact will occur the ESC system showed to stabilize the automobile faster and it is shown that an expected improvement in stabilization time is between 40 to 62 percent. It was also seen during this part of the scenario that 2 percent loss of control occurred with an active ESC system and 45 percent without.

Nyckelord
Keywords

ESC, driving simulator, vehicle dynamics, brake dynamics, simulator study

Abstract

The objective of this thesis is to implement a basic, yet realistic, ESC system into the VTI simulator environment. This system is then validated to assure that it is working properly and provides a realistic behavior.

The implemented ESC system is used in a study, where the ESC system could be turned on and off, to evaluate the benefits of an ESC system after a side impact. This study shows that an ESC system may aid the driver in such a critical situation when the driver is unaware that a side impact will occur. With the ESC system active no driver lost control while with the system inactive there were five drivers that lost control, but deviations in initial speed give statistical difficulties, thus more tests are needed. In the case where the driver knows that an impact will occur the ESC system showed to stabilize the automobile faster and it is shown that an expected improvement in stabilization time is between 40 to 62 percent. It was also seen during this part of the scenario that 2 percent loss of control occurred with an active ESC system and 45 percent without.

Sammanfattning

Målet med detta exjobb är att implementera ett grundläggande och realistisk antisladdsystem i VTIs simulatormiljö. Detta antisalddsystem har validerats för att säkerställa att det fungerar som förväntat och beter sig realistiskt.

Det implementerade antisladdsystemet används sedan i en studie, där antisladdsystemet kan slås av eller på, för att testa nyttan av ett antisladdsystem efter en sidokrock. Denna studie visar att ett antisladdsystem kan hjälpa en förare som inte är beredd på att en sidokollision kommer inträffa. Med antisladdsystemet aktivt så förlorade ingen förare kontrollen över bilen medans utan systemet så var det fem förare som förlorade kontrollen. Dock så ger skillnader i ingångshastighet statiska problem och fler tester skulle behövas. Om föraren var medveten om sidokollisionen så visade det sig att antisladdsystemt stabiliserar bilen snabbare och en förväntad förbättring av stabilitetstiden ligger mellan 40 till 62 procent. Under denna del så såg man också att förare tappade kontrollen under 2 procent av alla försök med ett antisladdsystem aktivt medans utan ett antisladd så var siffran 45 procent.

Acknowledgments

Over the course of this thesis there have been a lot of people involved which must be mentioned. First I would like to thank VTI and Jonas Jansson at VTI for giving me the opportunity to do this thesis. I would also like to thank people at the FTS group at VTI (Albert, Anne, Björn, Fredrik, Laban, Göran, Håkan J, Håkan S, Martin, Mats, Mattias and Staffan) for explaining the simulator environment and a lot of practical guidance using the simulator, and for helping as test drivers during the implementation of the ESC system and the scenario. There were more people at VTI that participated as test drivers in this stage of development which also deserves a thank.

During the study the group of friends and volunteers participating must be thanked, without you the study would not have been possible and I also hope that every test driver saw it as a good experience driving in an advanced driving simulator in a critical situation.

A special thank to both my supervisors (Erik Hellström and Jonas Jansson) for interesting discussions throughout the thesis.

I would also like to thank every person at VTI for a kind welcoming and interesting discussions on all kinds of topics throughout my stay during this thesis, and thanks to family and friends for support and also for helping me to put the thesis aside from time to time.

Last but not least a big thank to my girlfriend for all the support, and a small thank to our cat for his silent understanding.

Anders Andersson

Contents

Chapter 1

Introduction

1.1 Introduction to ESC

ESC (Electronic Stability Control) is an electronic safety system which helps the driver to maintain control of the automobile during a maneuver where the automobile starts to slip sideways. The ESC system consists of a closed loop controlling the automobile usually by adjusting the brake pressure and engine torque. How the brake pressure is applied may vary between implementations, and also the engine torque adjustments will vary between implementations or may even not be implemented. Today the ESC is common to be included when you buy a new car in Sweden, and according to [6] Europe are striving to make ESC standard for automobiles from year 2012.

But why is ESC that important? Studies based on crash statistics have shown that it reduces the amount of severe and fatal accidents, see for example [5]. According to [10] the effectiveness of the ESC is at least 13% for car occupants in all types of crashes with serious or fatal outcome, and in [6] they estimate that it will reduce road deaths in Europe by up to 2500 a year. There have also been simulator studies (for example [21]) that show similar or even better results and a summarization of benefits from more studies can be found in [11]. There is also a big difference in the effectiveness depending on the road tire interaction, for examlpe there is a big difference between asphalt and gravel. The weather also plays a big role in the interaction, since ice and snow make a huge difference in the tire adhesion. But one should not forget that while the effectiveness is larger under more difficulty conditions the ESC is still valuable during normal driving conditions, e.g. highway driving on a cloudy summer day.

So how does it work? As mentioned, the ESC can apply individual brake force to all wheels. The ESC system may also control the engine by, for example, controlling the throttle or perhaps it may control the ignition and thereby reduce the engine torque. Starting with the braking force, it is usually delivered by a brake system that controls the brake pressure. This means that by controlling the pressures, the ESC system can brake one or more wheels as desired. But how should the pressure be applied? A basic way to do it is to brake one wheel at a time and then brake the wheel that makes the most difference while it still is safe to brake. But why do we also want to control the engine? The answer is that since a common situation where you get the automobile to slip is when driving to fast or accelerating in a turn, and we want the ESC system to realize that the turning speed is too high with respect to the wheel grip and then slow down. Thus, there are different kinds of methods and combinations of methods to make it safer for the driver when driving at the limits of the tire-road friction.

So when there are so much research in this area already done and the positive effects are documented, why then make another work on this subject? Well, the ESC system has means to influence the vehicle dynamics, and thus it is crucial that sensors and actuators used by the ESC system works properly. To ensure this, there are plausibility controls checking the sensor values. When a sensor gets a value where the plausibility control activates, the ESC system shuts down due to a sensor malfunction. One situation where this might happen is when the automobile is hit sideways during driving, since then the automobile will have a sudden lateral acceleration which may trigger the plausibility control and shut down the ESC system. One goal of this thesis is therefore to study if there are any benefits of having the ESC system active during a side collision.

Similar studies have been made, see for example [16] or [17], where positive effects from an ESC system has been noted. Based on these works, it is expected to see a benefit with an ESC system in this study as well.

1.2 The goal of this thesis

The goal of this thesis is to develop, implement and validate a basic automobile ESC system into SIM-3 at VTI. The ESC system should be implemented as a plugin and an internal documentation should be created. The ESC system should then be used for a study where the driver is presented with a side collision scenario both aware and unaware where the positive effects of the ESC system are investigated.

1.3 Methods used

To understand how an ESC system works, a literature study has been made using both books and articles and discussions with people with knowledge of an ESC system. From this a design decision were made and this design was implemented into the SIM-3 environment. Parameters for the ESC system in the simulator has been estimated based on tests within the simulator with test drivers. For the simulation study, articles have been studied and discussions have been made with people with knowledge of simulator experiments. From this, a scenario was created which were adopted to test drivers opinions testing the scenario improving the scenario. The study was then performed using friends and volunteers as test drivers and the results were analyzed.

1.4 Limitations

Since the aim is to implement a basic ESC system, there are a lot of limitations made to the ESC system and the brake dynamics further described in the theory chapter. Due to time and schedule reasons, the test persons used in the small study in this thesis will be friends and other volunteers participating freely when there was access to SIM-3.

1.5 Thesis outline

Chapter 1 A short introduction to this thesis.

Chapter 2 A introduction to the Simulator III environment.

Chapter 3 The implemented ESC system used in the automobile model.

Chapter 4 Explains brake dynamics and why it is important to implement.

Chapter 5 The validation of the ESC system and the brake dynamics.

Chapter 6 The outline of the study and data acquired from it.

Chapter 7 Conclusions drawn from the validation of the implementation and from the results from the study made.

Chapter 2

The simulator environment

The simulator used in this study is the VTI Simulator III, or shortly SIM-3. This simulator was built in 2004 and is mainly used to simulate car dynamics. This is the simulator the ESC software has been developed for and the simulator used in the study. To get a little more familiar with SIM-3 this chapter is a short introduction to SIM-3 and the parts focused on in this thesis.

2.1 SIM-3 hardware system

Since the focus is on the ESC system and the scenario, the introduction are on the components used to get the ESC system and the scenario to be realistic. This include motion of the SIM-3, how the brake system hardware interacts with the software, the sound, and visual feedback.

2.1.1 SIM-3 dynamics system

The simulator is mounted on a band which uses a hydraulic layer to get a smooth sideways movement, see Figure 2.1. This band can deliver a linear speed of 4 m/s and an acceleration of 0.8 g. On this band, a platform has been built and is used to tip and turn the cabin in several directions, performance limits are a pitch angle of -9 to 14 degrees and a roll angle of ± 24 degrees. The cabin is also mounted on a vibration table which may be used to tip or shake the automobile. This vibration table can deliver a vertical and longitudinal motion both of ± 6 cm. A pitch angle of ± 3 degrees and a roll angle of ± 6 degrees can also be achieved.

2.1.2 SIM-3 brake system

The SIM-3 brake system used is a real production system with disc brakes modified to fit the simulator environment. These modifications consist of the removal of the rear of the car, thus the hydraulic system has been changed and the brakes are all mounted on the right front side of the cabin, see Figure 2.2. We notice that there are not an ESC system in hardware and therefore no actuators to modify

Figure 2.1. The SIM-3 lateral motion and cabin.

the pressure in the brakes, thus the brake dynamics for the ESC system are done in software. The brake system also contains an ABS system in hardware which during this thesis will be turned off. This decision is motivated by the problems occurring of making a hardware ABS work together with a software ESC, thus time is saved.

2.1.3 SIM-3 perceptual systems

There are also systems present to give perceptual feedback to the driver when driving such as visual, sound and vibrations feedback among other things. To present the scenario to the test drivers the parts focused on here are the visual system and the sound system.

Visual system

The visual system is the system that presents the driving environment to the driver. This is mainly done with the three projected views covering 120 degrees of sight of the driver, and also three smaller screens as mirrors inside and outside the cabin. To also let the operator see what the driver sees, the same graphics are presented to the operator on six screens. To handle all these graphics, six computers are used which are accessed through the network. These projected views are what the driver will see while driving, and this will be used to create a realistic environment to the driver during the scenario used in the study.

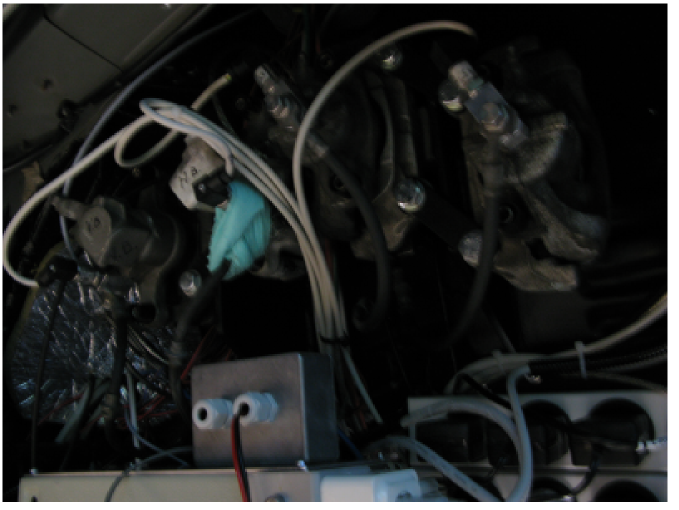

Figure 2.2. The SIM-3 disc brakes mounted on the side of the cabin.

Sound system

Another important aspect to create an experience of realism for the driver is the sound system, for example a feeling of wind and engine sound. This system consists of five speakers, two speakers close to the windshield in the dashboard, one speaker in each of the front doors, and one rear speaker. The speakers are controlled by a separate computer which can play sound in any of the five speakers. This computer dedicated to the control of the sound interacts with its environment through the network.

2.2 SIM-3 software system

To make all these subsystems work together a framework written in C++ is used. Closer to the hardware a lot of code is written in C which interacts with the framework. Since the development of the simulator has been an ongoing process there are also parts written in Fortran which are really stable since they are well tested. There are also XML interfaces to specify input to different parts in the software. The code written in this thesis is written as a plugin with a XML interface to make it easier to use the code only when desired. Also a lot of parameters to the implemented ESC system can be changed easily through the XML interface.

Chapter 3

The ESC system

The definition of an ESC system from [14]:

- ESC augments vehicle directional stability by applying and adjusting the vehicle brakes individually to induce correcting yaw torques to the vehicle.
- ESC is a computer-controlled system, which uses a close-loop algorithm to limit understeer and oversteer of the vehicle when appropriate.
- ESC has means to determine vehicle yaw rate and to estimate vehicle sideslip.
- ESC has means to monitor driver steering input.
- ESC is operational over the full speed range of the vehicle (except below a low speed threshold where loss of control is unlikely).

With this definition, we need to control the brakes individually by using a computer controlled system using the yaw rate and sideslip angle. The speed and steering input from the driver as input to our system will also need to be monitored. This definition then provides us with the basis of our ESC system but needs additions to make it a complete system. What this definition do not take into account is the drivers reaction when the system intervenes and how the automobile equipped with the ESC system ”feels” like. It is also fuel inefficient to have the ESC system active all the time and therefore we add the following criterions for our ESC system:

- ESC intervention does not induce panic to the driver.
- ESC does not intervene during normal driving.

Now when we know what the expectations are from the ESC system we have to make sure that it works in conjunction with all the other systems that might be present or that the other systems do not intervene with the ESC system. For example, the ABS system has to fully function when there is an ESC system present in a production automobile. This will be an implementation specific requirement and will not be completed in this work due to software and hardware interaction problems, but it is still very important to consider.

Also remember that since we are working in a simulator environment, there have been made simplifications to be able to run it in real time while still providing realistic automobile behavior. These simplifications are:

- There are no sensor simulation, thus we exactly know the vehicle state all the time.
- Front wheel angle is a linear function of the steering wheel.
- The brake pedal pressure is disabled during an ESC intervention.
- Engine intervention is done by disabling the gas pedal.

With all this in mind we continue with the different parts of the ESC system implemented.

3.1 Calculate the driver maneuver intention

The first thing needed for our ESC system to work is to find out what path the driver intends to drive. Knowing this path is crucial because otherwise we do not know if the automobile behaves as intended or not, thus we conclude that the desired model takes input from the driver and generates an intended path.

3.1.1 Desired model, input and output

A design decision that the implemented ESC system should resemble an ESC system in a production automobile motivates the choice of the steering wheel angle used as input. This input is also suitable since in our simulator environment we have easy access to this input. From this input an output that describes the path is wanted, two common variables to decide this is the automobile yaw rate and the automobile side slip commonly derived through a reduced linearized single-track model. This approach can, with some variations, be seen in [18] and [19] and this will be the approach used in this thesis.

3.1.2 Reduced linearized single-track model

The reduced linearized single-track model, also known as the ”bicycle model”, with linearized slip angles is a well known model [7], [9] or [22], and it is illustrated in Figure 3.1. The nomenclature in this thesis is the same nomenclature as in [9], and the derived state equations are:

$$\begin{bmatrix} \dot{\beta} \\ \ddot{\Psi} \end{bmatrix} = \begin{bmatrix} -\dfrac{c_F + c_R}{m_{CoG} v_{CoG}} & \dfrac{c_R l_R - c_F l_F}{m_{CoG} v_{CoG}^2} - 1 \\ \dfrac{c_R l_R - c_F l_F}{J_Z} & -\dfrac{c_R l_R^2 - c_F l_F^2}{J_Z v_{CoG}} \end{bmatrix} \begin{bmatrix} \beta \\ \dot{\Psi} \end{bmatrix} + \begin{bmatrix} \dfrac{c_F}{m_{CoG} v_{CoG}} \\ \dfrac{c_F l_F}{J_Z} \end{bmatrix} \delta_W \qquad (3.1)$$

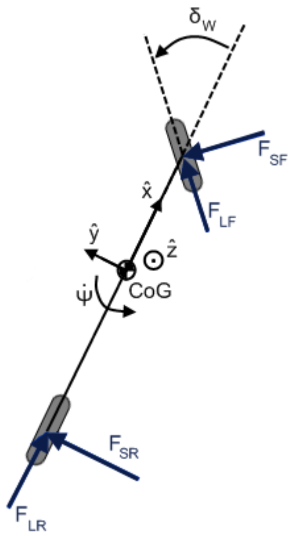

Figure 3.1. The bicycle model.

Here β is defined as:

$$\beta \equiv \arctan\left(\frac{v_Y}{v_X}\right) \quad (3.2)$$

The automobile dimensions are shown in Figure 3.2, J_Z is the moment of inertia about the vertical axis, m_{CoG} is the vehicle mass, v_{CoG} is the automobile velocity at its center of gravity (CoG), v_X and v_Y are the longitudinal and lateral speed, c_F and c_R is the front and rear tire cornering stiffness for each pair of wheels and δ_W is the wheel turn angle.

3.1.3 Derivation of reference values

From these state equations, functions describing the yaw rate and sideslip using the steer wheel angle are desired. One from steer wheel angle to the yaw rate and one from steer wheel angle to the side slip. To do this in a simplified way, we consider the stationary state, i.e. $\ddot{\Psi} = 0$ and $\dot{\beta} = 0$. Another simplification made is that the longitudinal speed is dominant over the lateral speed, i.e. $v_{CoG} = v_X$. Now the model use the wheel turn angle and not the steer wheel angle and once more for simplicity a linear relationship is used, thus $\delta_W i_s = \delta_S$ where δ_S is the steer wheel angle and i_s is the linear transmission coefficient from steering wheel angle to wheel angle. Also to correct for offset errors in the vehicle model we add offset parameters ($\dot{\Psi}_{off}$ and β_{off}) to the reference values. With all these simplifications, we arrive at:

$$\dot{\Psi}_{ref} = \frac{1}{l}\frac{v_X}{1+\frac{v_X^2}{v_{ch}^2}}\frac{\delta_S}{i_s} + \dot{\Psi}_{off} \tag{3.3a}$$

$$\beta_{ref} = \frac{1}{l}\frac{l_R - \frac{l_F m_{CoG} v_X^2}{c_R l}}{1+\frac{v_X^2}{v_{ch}^2}}\frac{\delta_S}{i_s} + \beta_{off} \tag{3.3b}$$

Here v_{ch}^2 is the characteristic speed and is defined as:

$$v_{ch}^2 \equiv \frac{c_F c_R l^2}{m_{CoG}(c_R l_R - c_F l_F)} \tag{3.4}$$

Equations (3.3a) and (3.3b) are implemented in the simulator where a measured v_{ch} is used, i.e., we do not calculate it using Equation (3.4). Parameters needed for acquiring the reference values during simulation are then l_F, l_R, c_R, v_X, v_{ch}, m_{CoG}, $\dot{\Psi}_{off}$, β_{off}, i_s, and δ_W where $l = l_F + l_R$. v_X and δ_W are functions of time and needs to be updated continuously during simulation.

3.2 Control law

Knowing the driver desired path, a control strategy that control the automobile back on this path if the automobile leaves the path has to be implemented. We have chosen to use a PD controller due to the fact that it is a basic implementation that gives good enough results. Remember that we are in a simulator environment where the exact values of the yaw rate and the side slip are known and therefore the error signal used is:

$$e_n = \dot{\Psi}_{ref} - \dot{\Psi} + \xi(\beta_{ref} - \beta) \tag{3.5}$$

From this signal we then use the time discrete control law:

$$M_{des} = K_p e_n + T_d \frac{e_n - e_{n-1}}{T_s} \tag{3.6}$$

where K_p, T_d and ξ are control parameters and T_s is the period between samples in the simulator.

3.3 Applying correction torque

Now we want a simple method for applying the desired torque. When looking at our definition of an ESC system, as stated in the beginning of this chapter, we want to actuate this torque by applying braking force. Therefore, we need to make two decisions: Which wheels should we brake and how much pressure should we apply? Here we choose to apply pressure only to one wheel at a time which also

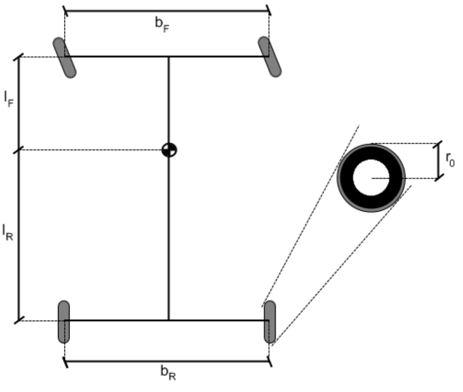

Figure 3.2. Car parameters.

means that we want this pressure to give us our desired torque, or as close to it as possible.

We do also have a restriction on our implementation since we do not want the ESC system to generate a small brake pressure all the time and thus we use a limit on the control error, given in Equation (3.5). This limit will be considered as a control parameter since it will affect the controller, and to prevent the system from being turned on and off frequently we use different limits dependent on if the system is active or not. These limits are given in Equation (3.7).

$$\text{ESC system inactive: } e_n = \begin{cases} 0 & \text{if } |e_n| < e_{high,limit} \\ e_n & \text{otherwise} \end{cases} \tag{3.7a}$$

$$\text{ESC system active: } e_n = \begin{cases} 0 & \text{if } |e_n| < e_{low,limit} \\ e_n & \text{otherwise} \end{cases} \tag{3.7b}$$

To decide when to activate and deactivate the ESC system, we use the same logics, i.e., we activate the ESC system when the ESC system is inactive and the control error reaches a value above the high limit and we turn the ESC system off when the ESC system is active and the control error has a value below the low limit. This is to assure us that the system is not turned on and off frequently and that if the ESC system activates, the system is active a little longer further stabilizing the automobile.

To make the system even more effective the throttle will be used to not allow the driver to accelerate during an ESC intervention. In a more realistic way, usually the ESC system has engine intervention to get a quicker response. This is something we will not do.

3.3.1 Decision for one wheel brake

When only braking one wheel we need to know which wheel to brake. We will use the same approach as in [2] which is:

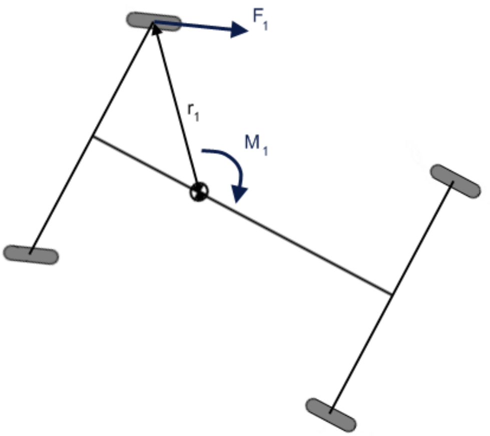

Figure 3.3. Distance to brake force.

- Turning left and understeering: brake rear left
- Turning left and oversteering: brake front right
- Turning right and understeering: brake rear right
- Turning right and oversteering: brake front left

So when we know which wheel to brake, how much should we brake? We know the desired torque and we know the distance to the wheels since we have the geometry, as specified in Figure 3.2, and then we get the desired force at the wheel as:

$$\bar{M}_{des} = \bar{r} \times \bar{F}_{des} \tag{3.8}$$

Here M_{des} is the desired torque from the control algorithm and $\bar{r}$ is the vector from the automobile CoG to the contact point of the force F_{des} at the wheel. Usually the contact point for the force from the wheel is a little behind the center of the wheel but we will neglect this effect.

An illustration of how torque and a force relates in a particular case is seen in Figure 3.3 where the torque is in negative direction. Notice that since we have front wheel steering, we will have different expressions for the front and rear wheels.

3.3.2 Applying brake pressure

The desired force as seen in Equation (3.8) should be realized by braking the appropriate wheel, and thus a relationship between desired force to desired pressure is needed. This relationship between force and pressure will be given by:

$$P_{des} = \frac{r_0 10^6}{BRT} F_{des} \tag{3.9}$$

Here r_0 is the original wheel radius, the factor 10^6 is for converting from [MPa] to [Pa] and BRT is the linearized brake to torque factor given by measured data on the brake system and will be further explained below. With this approach, we once again have a linear relationship which will be another simplification. Another simplification is that we use the original wheel radius thus neglecting any deformation.

Finally, the equations describing the total behavior is (FL is front left, FR is front right, RL is rear left and RR is rear right):

$$FL : P_{des} = \frac{r_0 10^6}{BRT_{FL}} \frac{M_{des}}{-l_F sin\delta_W + \frac{b_F}{2} cos\delta_W} \tag{3.10a}$$

$$FR : P_{des} = \frac{r_0 10^6}{BRT_{FR}} \frac{M_{des}}{-l_F sin\delta_W - \frac{b_F}{2} cos\delta_W} \tag{3.10b}$$

$$RL : P_{des} = \frac{r_0 10^6}{BRT_{RL}} \frac{2M_{des}}{b_R} \tag{3.10c}$$

$$RR : P_{des} = \frac{r_0 10^6}{BRT_{RR}} \frac{2M_{des}}{b_R} \tag{3.10d}$$

Last but not least, what happens if the controller asks for a brake pressure which would generate a force which would not be possible to get if we are driving on a low friction surface like ice? In our implementation, the wheels would lock and slide on the surface. This is an undesirable behavior and there should be systems securing that this does not occur, such as an ABS system. Our approach to this problem is that even though we slide with the wheel we still get a stabilizing yaw torque.

The parameter BRT

The use of the parameter BRT comes from the fact that the hardware in the simulator does not contain the rear of the automobile and, as mentioned, this parameter has been estimated from data to simulate a complete brake system. The characteristics of that data is shown in Figure 3.4. This is from a test where the brake pedal in the car is pushed while measuring pressure, and torque. Here we see that when the master cylinder pressure activates, the torque increases in a linear way with only a constant needed to describe the torque at the wheels. The reason why the torque from the rear wheels is smaller than the front wheels is because there is a valve decreasing the pressure to the rear wheels. Two reasons for this is that it is more effective to put more pressure on the front wheels due to the fact that during heavy braking the main weight is on the front wheels and it is also for stability since if the rear wheels lock before the front wheels the result is usually skidding with the automobile.

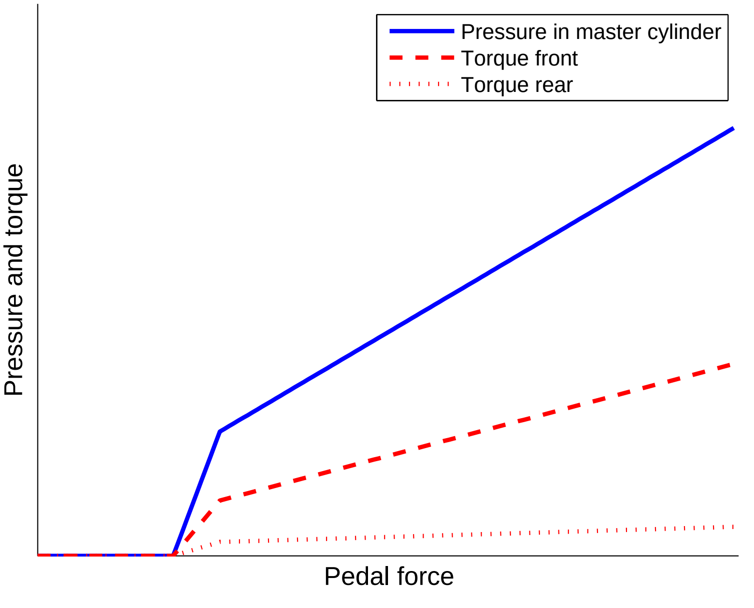

Figure 3.4. The characteristics of data used to calculate the parameter BRT for front and rear wheels.

Chapter 4

Brake dynamics

When the ESC system has specified how much pressure it wants, the brake system should apply it as fast as possible. But brake systems with ESC used in automobiles today have brake dynamics which has to be accounted for. The approach in this thesis is to keep it simple while still providing reasonable results, thus a first order system was chosen to represent the brake dynamics.

4.1 Brake dynamics as a first order system

In a production automobile there will be brake dynamics meaning that the pressure in the brakes will have to be built up and will not be instant. There will also be a difference between building up pressure and releasing pressure since in a production system the pump building up pressure will be slower than the valves used to release the pressure. To correct for these time delays in a production automobile we add a first order systems with a time constant. For every wheel and the ESC brake pump, our first order system will be used but with different time constants depending on the situation. A first order system is given by:

$$G(s) = \frac{1}{\tau_s s + 1} \tag{4.1}$$

where τ_s is the time constant. To make this system discrete we discretize exactly [8], which gives the system:

$$P_{n+1} = e^{\frac{-T_s}{\tau_s}} P_n + (1 - e^{\frac{-T_s}{\tau_s}}) P_{des} \tag{4.2}$$

where τ_s is the time constant, P_n is the current brake pressure, T_s is the sample period time and P_{des} is the desired pressure coming from the ESC system.

4.2 Measuring the time constant

Since there is a production brake system in the vehicle in the simulator, a step response from that brake system has been made. This step response test proceeds

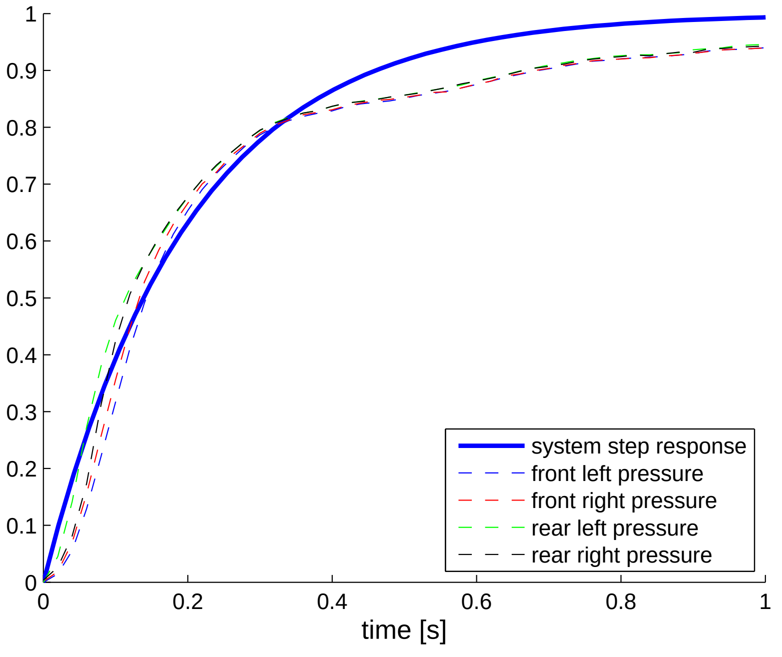

Figure 4.1. Measured brake data from a brake pedal step response and our system with a time constant of 0.2. Notice that the maximum pressure level of the brake system has been used to scale down the logged brake pressure levels to be between 0 and 1.

as to first accelerate the vehicle up to high speed on a high friction surface and then the driver presses as hard and fast as possible on the pedal. A test driver doing this will not be able to produce the brake step response instantly but will be considered to be fast enough. The brake pressures induced by the pressing on the brake pedal is then measured and logged. Data from this log is then used to approximate an appropriate time constant to our first order system. Data from a step response to the implemented first order system building up pressure and measured data from the brake test is shown in Figure 4.1.

In a real production system, the pump used by the ESC system will most likely not be able to produce the same pressure as fast as a driver pushing the brake pedal. This would mean that our measured time constant from this test will be too fast and our implemented system in the simulator will be faster than a production system in an automobile. This is something we are aware of and the implementation in the simulator is such that this time constant can be changed in real time.

4.3 The complete brake system

When designing the complete brake system the model has been the brake system in [20] which is called the second generation hydraulic system. Here the pump is able to independently distribute pressure to all four wheels through valves. Therefore, the pump can distribute its current pressure to any wheel/wheels. The time it takes for the valves to open and close is much faster than the dynamics in the pump, thus the pump dynamic will be dominant, and in our implementation the dynamics with the pressure at the wheels is at least a factor 10 faster. The complete system then consists of a pump which starts to build up pressure when an ESC intervention occurs. This pump then delivers pressure to a wheel depending on the logics of the ESC system, and while providing pressure the pump does not loose any pressure while still building up pressure to its maximum level. Shortly, the ESC system may not be able to provide wanted pressure in the beginning of an intervention but after some time the system can provide desired pressure almost instantly. When the ESC system deactivates, the pressure in the pump will not be released immediately. Instead, the pump will continue to build up pressure for a short amount of time, thus this amount of time is a design variable.

Chapter 5

Validating the model

With our ESC system implemented as specified, we have to make sure that the complete ESC system works as intended (a realistic ESC system), thus validation is a natural step. To validate our model, we start by validating different parts of the system and then validate the complete system.

5.1 Validating the reference values

To validate that our calculated reference values correspond to normal driving on a high friction surface a test during these conditions was made. Because the linearized model is meant to describe the automobile dynamics during these conditions a good correspondence between the reference values and the logged data from the SIM-3 automobile model is expected. The test made was driving on a typical Swedish country road, while not making any sudden maneuvers, in 50-90 km/h while overtaking slower vehicles in the simulator. This test was done by a test driver before the study, and data from a part of this test is shown in Figure 5.1.

As seen in Figure 5.1 the reference values follow the ”measured” values with some deviations. The main reason for this is that the parameters used in our implementation of the ESC system is not the same as the simulator model and another reason is that the simulation model used is a more complete vehicle model. The decision to use parameters that differs is that in reality this will usually be the case. For example the mass of the automobile is a parameter such that it will change continuously during driving in an automobile with a combustion engine due to the combustion of fuel. For a small example on how an error in automobile mass effects the reference values, see Example 5.1. Another parameters that will differ are the tire cornering stiffness coefficients due to wear and also if the driver shifts tires between winter and summer. Since there are a lot of aspects that may change parameters used by the ESC system quickly or slowly during the course of time a small error in the reference values are expected, thus the Figure 5.1 shows a realistic behavior. In this figure we also notice that the dynamics for the side slip is not modeled but this is also expected since our ESC system uses a static

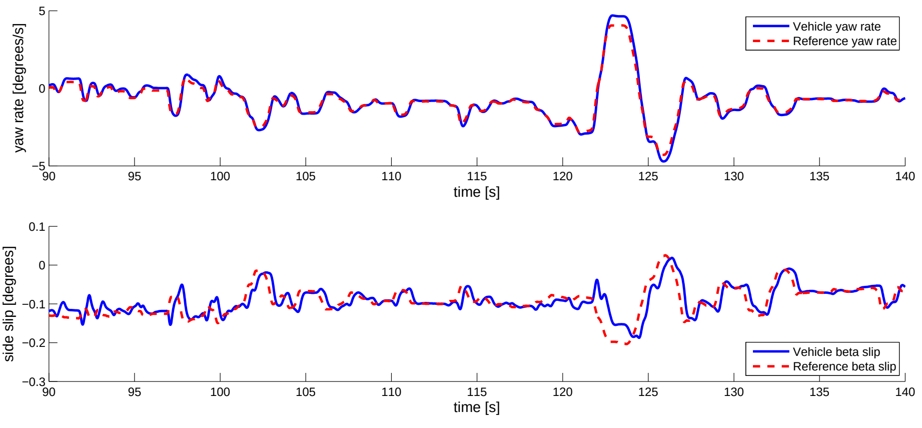

Figure 5.1. Calculated reference values and ”measured” data during a normal drive.

model.

This validation consider when driving normal, but how does the model behave when we drive more at the limits of the model? To see where this model has its limits in lateral acceleration, an increasing steering wheel angle test is done and results from this test are seen in the appendix.

Example 5.1: Automobile mass

Consider Equation (3.3). If we in this equation have a percentage error (ϵ_m) in the automobile mass we could introduce this error as:

$$v_{ch,\epsilon}^2 \equiv \frac{v_{ch}^2}{1+\epsilon_m} \tag{5.1}$$

Here we see that the characteristic speed will depend on an error in the automobile mass and if the driver drives at this speed we get our maximum yaw rate as:

$$\dot{\Psi}_{ref,\epsilon}(v_{ch,\epsilon}) = \frac{v_{ch,\epsilon}}{2l}\frac{\delta_S}{i_s} = \frac{1}{\sqrt{1+\epsilon_m}}\frac{v_{ch}}{2l}\frac{\delta_S}{i_s} = \frac{\dot{\Psi}_{ref}(v_{ch})}{\sqrt{1+\epsilon_m}} \tag{5.2}$$

Here we see that the error will relate to the maximum yaw rate without an error as an inverted square root. To add numbers lets say that we have an error of 10 percent more mass which will result in an error of approximately 5 percent. If our automobile has a mass of 1400 kg an error of 10 percent would mean 140 kg which could be driving with two friends and is thus a realistic situation.

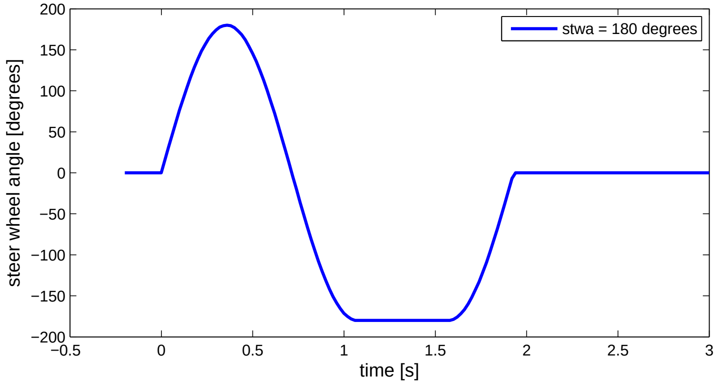

Figure 5.2. A 0.7 Hz sine with a dwell maneuver with a maximum steering wheel angle input at 180 degrees.

5.2 Validating the braking system

When validating the implemented braking system there are at least two tests that need to be done, first a validation that the ESC system brake logic decides to brake wheels in a correct manner, and second that the brake pressure takes time to build up. The test used to validate both these cases is a sine with a dwell maneuver where we do the maneuver with the steering both to the left and to the right. This maneuver is seen in Figure 5.2 and is further described in the appendix.

5.2.1 Validating brake actuating

During a sine with a dwell maneuver to the left we log desired brake pressure from the decision logics and the actual brake pressure at each wheel, see Figure 5.3. Of interest here are the desired pressure levels which show how the ESC system wants to control the brakes. When the system starts to turn left, the system wants to brake the rear left wheel. This behavior is wanted since the maneuver is done at a speed where we get a high slip and therefore the car understeers in a left turn, thus the logic should help to increase the turning speed which it does. After that, the front right brake starts to brake which is also desired behavior since we have achieved a yaw rate to the left which indicates that the car is turning left and then tries to turn right. The ESC system will continue to brake this wheel until a yaw rate to the right is achieved where the decision will be to brake the rear right wheel instead of the front right. This since the achieved yaw rate to the right is smaller than the desired yaw rate and as seen the correct brake is used during this small amount of time. After that we may have braked too much and gained a too large yaw rate to the right which then has to be stopped. This will require the front left brake to be used, which it is. After all this we are at 1.07 s which is where the dwell starts in the sine with dwell maneuver, and all of our cases have been covered. Notice that the maneuver is only shown done to the left and

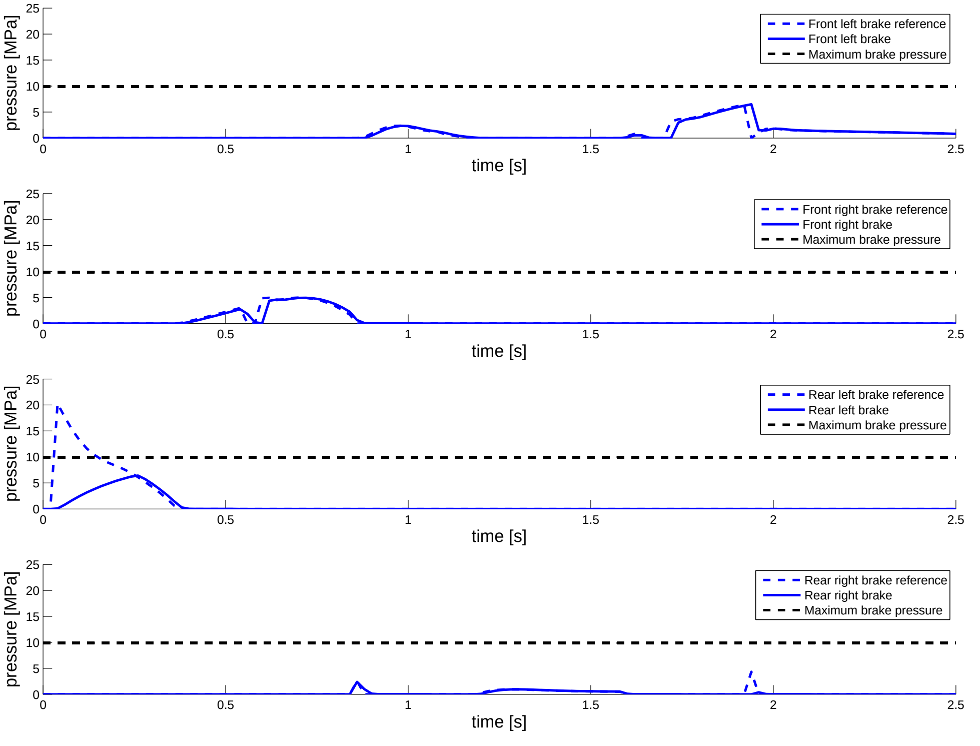

Figure 5.3. Validation of brake actuation and dynamics during a 0.7 Hz sine with a dwell maneuver with an amplitude of 230 degrees and the steering starts to the left.

there could be differences in implementation that makes it differ when starting to the left or the right. This will not be shown but tests have been done in both directions showing the same characteristics, correctly braking appropriate wheels.

5.2.2 Validating the brake dynamics

Implemented brake dynamics will also be validated during the same sine with a dwell maneuver shown in Figure 5.3, thus the data is used again since the reference brake pressures and the actual brake pressures were logged. Here we notice that first when the maneuver starts we do not have any pressure in our pump and we start to build up pressure, this is clearly visible since the reference value and the actual brake pressure differs. Also notice that the reference value takes a large step upwards directly in the beginning of the maneuver which is caused by the threshold activating the ESC system. To see more precisely we take a closer look at the control error during this sine with a dwell maneuver, see Figure 5.4. In

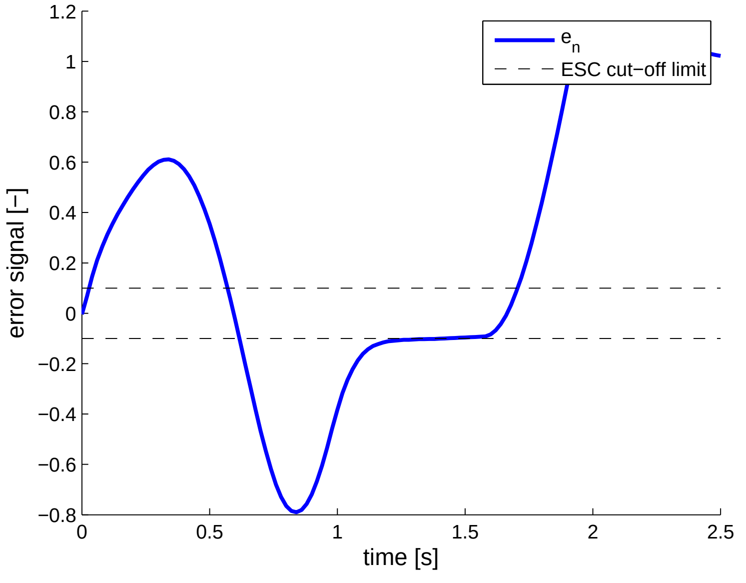

Figure 5.4. Logged control error during a 0.7 Hz sine with a dwell maneuver with an amplitude of 230 degrees.

the beginning we see that the derivative part is large, which will be the main contributor to the desired brake pressure. Since the error will give a zero desired pressure below the limits and a large value above the limit we get a desired pressure value that moves from zero to a large value. Also, since it is a rear tire the desired pressure is larger since it will be scaled down later in software due to the parameter BRT. After the initial activation of the brake pump system, the pump continues to build up pressure and may distribute it to the desired brake, this is seen in all the other cases where the brake pressure follows the desired pressure well. There are still a fast time constant and a time delay which makes the system not being able to follow the reference perfectly which is expected since there would be delays in a production brake system using valves pipes.

5.3 Validating the ESC cut-off limit

When designing the ESC system, parameters have been trimmed to make the system activate quite early to get a smooth intervention, but since a system that brakes when not needed will be energy inefficient, a validation of how often this occurs is needed. To do this we use the same data logged when validating the reference values and logged data is presented in Figure 5.5. As can be seen in this figure there is a margin to the cut-off limit which is desired. Note that this test will heavily depend on the driving style and therefore this will be a subjective test,

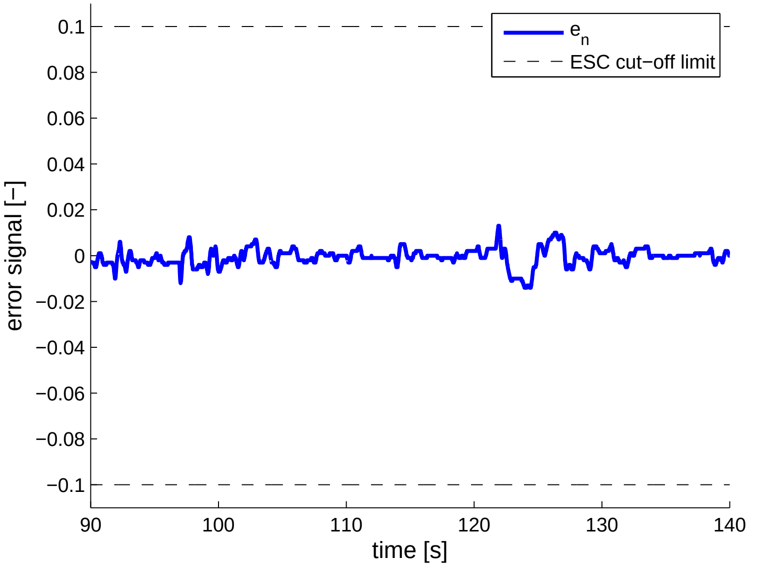

Figure 5.5. Data from tests when driving normal, i.e. overtaking cars and maintaining the speed limit on a high friction surface.

but with our design approach we design the system to not activate when driving calmly i.e. not being a sport setup that allows greater slip values without the ESC system intervening.

A situation where the error signal exceeds the limits is during a sine with a dwell maneuver which is already shown, see Figure 5.4. Here it is seen that the limits activates the ESC system early which was desired, and if we compare with the brake pressures, see Figure 5.3, it is seen that when the control error is below the limits there are no desired brake pressure.

5.4 Validating the ESC system

When validating the ESC system there are mainly two types of tests that have to be considered, they are understeering tests and oversteering tests. According to studies made by NHTSA [14] they recommend the use of the 0.7 Hz sine with a dwell maneuver seen in Figure 5.2 as an oversteering test and this will be the test used to validate the complete ESC system implemented. For an in depth description of the sine with a dwell maneuver, see the appendix. As for an understeering maneuver, none has been recommended. Tests with lane change maneuvers and slalom maneuvers have also been made and are also described below.

5.4.1 Parameter testing

A PD controller as the one used will need to be adjusted to fit the implementation and there are also a lot of other parameters that need to be set. This has been done in an iterative process where test drivers have been driving and then providing feedback, the feedback was analyzed and changes were implemented. The philosophy that a smooth intervention is desired has also been used here and if the tuning was to aggressive it has been tuned down. This iterative process was made before the study started.

The maneuvers the test drivers used were the double lane change and the slalom maneuver and results from these maneuvers are described below. It was also desired that these maneuvers would not stress the system too much, thus to be gentle against the simulator system and also not to introduce motion sickness to the test drivers.

The double lane change maneuver

The maneuvers used here are a mix of several maneuvers which are the ISO 3888, the ISO 3888-2 and the modified ISO 3888-2, where the ISO 3888-2 and modified ISO 3888-2 can be found in [11]. During early tests when the brake actuation were not completed, the brake pressure distribution between wheels were not finalized thus releasing the pressure when changing wheel to brake. Thus these maneuvers were found hard to get any accurate results from due to that test drivers learned how to steer to manage the maneuver almost as good without the ESC as with the ESC system active. Another problem was that the initial speed varied. To improve the accuracy in the results a cruise control could have been used or the brake system could have been more finalized, but instead the main maneuver to test the system was changed to the slalom maneuver where test drivers more easily felt the ESC system brake individual wheels. One more aspect has been to use a maneuver that do not stress the system to much, thus not introducing motion sickness to the test drivers so easily.

The slalom maneuver

The slalom maneuver has been the main maneuver to test the system and was used to set parameters. This maneuver consisted of five cones on a straight line, shown in Figure 5.6, where the driver was supposed to drive slalom between them. The friction used has been snow friction. This maneuver appeared to more easily give feedback from the drivers in the sense that they could feel the system work and the snow friction reduced the stress on the system thus only a few test drivers felt sick.

5.4.2 Results from the sine with a dwell

To verify that the complete system works as intended with the parameters used, a sine with a dwell maneuver test is done. Here we have chosen to do four test runs with fixed steering wheel inputs where we have chosen to use maximum steering

Figure 5.6. A snapshot of the layout of the slalom maneuver where the five cones have been encircled to get more visible.

wheel angles of 90, 120, 150 and 180 degrees. The test is done both with the ESC active and inactive, data from the tests is presented in Figure 5.7 and Figure 5.8.

So does the data in Figures 5.7 and 5.8 represent a realistic behavior? Begin with looking at the Figure 5.7, here we see that the yaw rate takes longer time to reach zero with increasing steering wheel angle. This is expected since a larger steering wheel angle results in a longer side slip. At a closer look we see that the stability criterions are probably not met when the maximal amplitude of the sine with a dwell is 180 degrees, which is the case, stability criterion one is not met. When the ESC system is active, Figure 5.8, we see that the yaw rate faster returns to zero, thus the ESC system stabilizes the automobile faster. Also notice that the stability criterions are all met, which was expected from the ESC system. Is this realistic? Similar plots can be seen in [13], which share the same characteristics. These plots are from tests with a production automobile, and thus the implemented ESC system behaves realisticly.

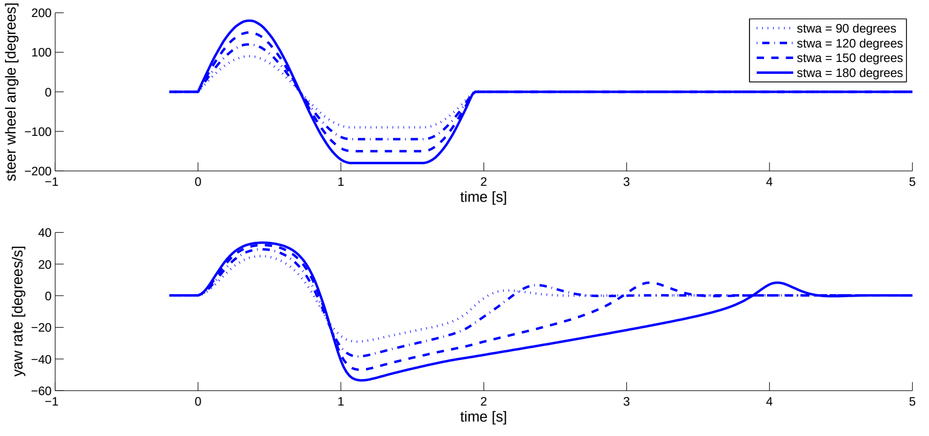

Figure 5.7. A sine with a dwell maneuver with the ESC system inactive.

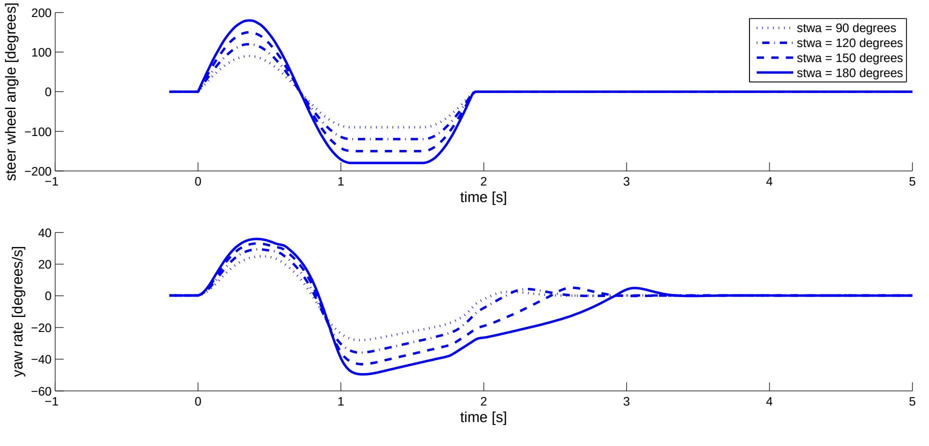

Figure 5.8. A sine with a dwell maneuver with the ESC system active.

Chapter 6

Simulation study

To further test if the ESC system assists the driver in a critical situation a study with test drivers was performed, which have been friends and volunteers. The critical situation chosen is a situation where the driver's car get affected with a force simulating a side car crash. Methods used to analyze the data logged from the study and the results from these methods are presented.

6.1 Outline of the simulation study

We look at the benefits of having an ESC system after a side impact. In a normal case, the ESC system will shut down when the sensors give values out of a predefined range, thus in a side crash the system might shut down. This study is divided into two parts where the first part will try to surprise the test driver in a critical situation and in the second part, the test driver will be prepared. During and after the study there will also be some questions asked to the test driver and the operator running the study will also take notes, the forms used are found in the appendix.

6.1.1 Part one of the study

In part one of the scenario we want to surprise the driver with something strong enough to trigger the ESC system. For this a rear side collision has been chosen, a car will slowly drive up from behind and try to overtake the test driver when a bus approaches and the car overtaking quickly turns back into the right lane and hits the test driver in the rear. The conditions are snow friction on a 70 km/h road with dense forest surrounding the road. A snapshot from this road is presented in Figure 6.1. This environment will likely make the driver a little more uncomfortable according to [1] and a faster reaction from the driver may be the case. The reason to use this environment anyway is that if the test driver senses that something will happen the driver should not easily be able to guess what. In more detail, part one of the study can be further divided into two parts which starts of with a part where there will not be any traffic to let the driver

Figure 6.1. A snapshot of the environment from the first part of the scenario.

get the feel of the simulator. After this warm-up part, there will be a 70 km/h road sign to remind the driver of the speed limit, and after this sign other cars will start to appear on the road. A car approaching from behind will also appear here but is placed far behind. Then the test driver will continue to drive during this common traffic while the car from behind slowly gets closer and closer. When the car behind gets close enough, it will start to overtake the test driver. Then a bus will be oncoming making the overtaking car trying to return to its lane fast resulting in the side crash. When the overtaking car has crashed into the test driver, the operator observes the test drivers actions and sees if the simulation aborts, or if the test driver leaves the road or if the test driver manages to stay on the road. This test is done with either the ESC system active or not, without the test driver knowing which.

6.1.2 Part two of the study

In part two of the study, the test driver is told that the vehicle will be affected by the same force as in part one when the test driver feels ready. Thus the driver tells the operator that he or she is ready and then the operator executes the side impact. The test driver is presented with a straight road and starts in the right lane and is told to drive at 70 km/h. If the ESC was active during part one, the ESC system is inactive during this first run. This test is then repeated 5 more times where the ESC system is turned on and off alternately resulting in 6 test runs with the ESC system active 3 times and inactive 3 times. This completes part two of the scenario.

During each of these side crashes, the test drivers were not explicitly told to regain control of the automobile and steer back to the right lane continuing driving, thus let the drivers react to the situation. If the driver stopped the automobile he or she was told to continue driving to repeat the side impact a few more times.

6.1.3 Influencing vehicle dynamics

In the scenario, the force affecting the automobile as the side impact should be realistic without any risk of damage to the test driver or the simulator system. This will limit us since the dynamics system can not provide immediate forces in a smooth way as would be more realistic during a crash. Also, the amplitude of the force during the push has to be considered since we want the test driver to be able to stay on the road regaining control of the automobile with an ESC system inactive.

Implementing the side to side low speed crash

The push implemented has foremost been implemented on feeling, thus drivers have tested the push and then provided feedback. If the push was too severe for the driver the force was scaled down, and if the push stressed the SIM-3 dynamics system to much it was remade or scaled down. This testing has been done with the intention that the driver drives at 70 km/h since this is the road speed limit used in the study. The push has been implemented as:

$$\bar{F}(t) = \frac{1 - cos(\omega t)}{2} F_{push}\hat{y} \tag{6.1}$$

Here ω is the angular frequency and F_{push} is the force creating the push. F_{push} is a parameter which can be increased or decreased, chosen to be positive or negative to affect the car to the right or left, and this is the parameter that has been adjusted to be appropriate for the test driver during the study. The impulse generated from this push is:

$$\int_{t_1}^{t_2} \bar{F}(t)\, dt = \bar{I} \tag{6.2}$$

In [4] a realistic way to model a front to rear low speed impact is discussed. In our case we will have a low speed side to side collision, but we assume these cases to be fairly the same. A comparison with the modeled crash is seen in Figure 6.2. One big difference between the more realistic push and the implemented is that the implemented push has a derivative in the beginning of the push that is zero to ease the stress on the simulator. Another big difference is that the time period for the push implemented will be 0.4 s. From [4] it is seen that a more realistic value would be around 0.17 s, but the stress on the system is more prioritized than using a realistic value. The magnitude of the impulse created, after the iterative process, is then 1200 Ns. For an estimate on how realistic this impulse is consider Example 6.1.

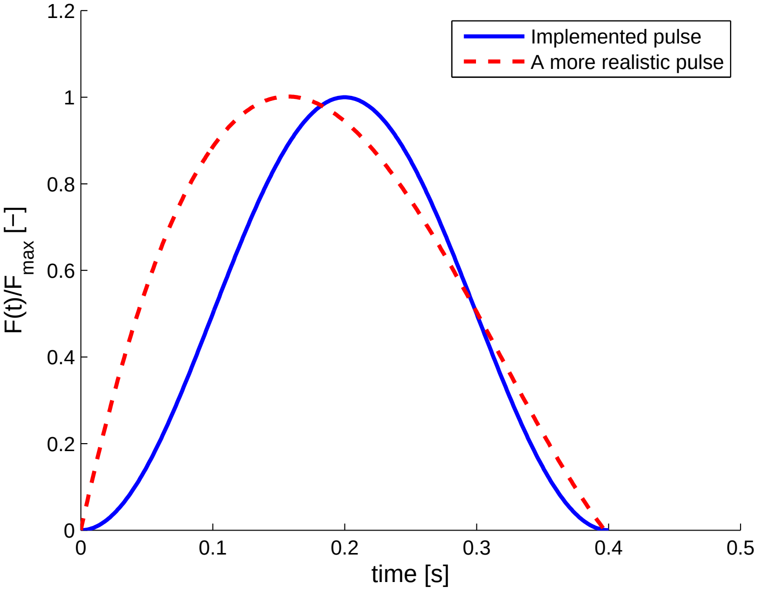

Figure 6.2. The implemented push to simulate a side impact and a more realistic push from a low speed front to rear crash. The push has in this figure been scaled with the maximal input force (F_{max}) during the push.

Example 6.1: A lateral speed estimate during a side collision

Since we have chosen to affect the vehicle in the simulation with a predefined impulse at 1200 Ns, one could ask if the magnitude of the impulse in the side to side crash is realistic. In this example we will consider at which speed an automobile of the same weight has to move sideways to be able to produce the chosen impulse and then make conclusions wether it is realistic or not. We begin with assumptions made about how the impulse is delivered:

- The side impact automobile is modeled as a point mass with a velocity.
- The automobile will not have an initial sideways velocity since it is driving on a straight road.
- A coefficient of restitution will be used.

Our impulse will be given from Equation (6.2) and we have chosen to use A and B as index for the driver's automobile and the automobile that crashes into driver. Everything that is before the impact is indexed as 1 and what happens after is indexed as 2.

The impulse depends on the difference in linear momentum and the following equation is used where $\bar{v}_{A,1}\hat{y} = 0$:

$$I_y = (\bar{p}_{A,2} - \bar{p}_{A,1})\hat{y} = (m_A\bar{v}_{A,2} - m_A\bar{v}_{A,1})\hat{y} = m_A\bar{v}_{A,2}\hat{y} \tag{6.3}$$

From the linear momentum, which is preserved, we get the following equation:

$$\bar{p}_{A,2} - \bar{p}_{A,1} = \bar{p}_{B,2} - \bar{p}_{B,1} \Rightarrow \bar{p}_{A,2} = \bar{p}_{B,2} - \bar{p}_{B,1} \tag{6.4}$$

The constant of restitution in the sideways impact is in $\hat{y}$ direction, thus given as:

$$e = \frac{\bar{v}_{A,2} \cdot \hat{y} - \bar{v}_{B,2} \cdot \hat{y}}{\bar{v}_{B,1} \cdot \hat{y} - \bar{v}_{A,1} \cdot \hat{y}} = \frac{\bar{v}_{A,2} \cdot \hat{y} - \bar{v}_{B,2} \cdot \hat{y}}{\bar{v}_{B,1} \cdot \hat{y}} \tag{6.5}$$

Solving these equations for $v_{B,1}$ in the $\hat{y}$ direction while also knowing that $m_A = m_B$ we get:

$$\bar{v}_{B,1} \cdot \hat{y} = I(\frac{1}{m_B} + \frac{1}{m_A})\frac{1}{1+e} = \frac{2I}{m_A}\frac{1}{1+e} \tag{6.6}$$

Which gives a numerical value for the speed $v_{B,1}$, which is the initial speed of the automobile driving sideways into the straight driving automobile, and causing the accident. Regarding the coefficient of restitution, a realistic value for a collision at speeds of 48 and 55 km/h according to [12] lies in the area of 0.1 to 0.13, we choose a value of 0.1. It is assumed that the vehicle mass is 1400 kg and remember that the impulse used in the simulation is 1200 Ns. This gives the initial speed as approximately 1.56 m/s, is this a realistic value?

Assume that the maximal lateral acceleration achieved on a slippery surface would be around 0.4 g which is approximately an acceleration of 3.9 m/s^2. To accelerate from zero lateral speed to 1.56 m/s would then take about 0.3 s, which is achievable. But this calculation does not consider that the automobile causing the side crash will rotate when turning. If the vehicle rotates, the lateral speed increases due to the longitudinal speed. So at what impact angle is the longitudinal speed rotated sideways to have a lateral speed of 1.56 m/s in the straight driving automobile? An automobile with a longitudinal speed of 70 km/h will then need an impact angle of 4.6 degrees, which is achievable. Both the sideways acceleration and the rotation of the automobile may achieve a lateral speed of 1.56 m/s, thus when they work together the lateral speed is easier achievable, and this would make it a realistic case.

But what if the collision instead of a side to side crash would be a moose running into the automobile, would this also be a realistic case? If the moose weight is 300 kg and we have the same numbers as before the initial speed of the moose has to be 4.42 m/s to produce the same impulse as before. According to unconfirmed sources there have been measurements of a moose running at approximately 13 m/s. If this would be true a speed of 4.42 m/s would not be of any problem to reach for a moose and it could then be considered realistic that this type of accident would produce the same impulse.

6.1.4 Perceptual aspects

When testing the system before the study, a lot of drivers complained of the lack of feedback from the ESC system. There is no feedback to the driver through the brake pedal, and when the ESC system was active there were no sound or visual feedback. Due to this, sound were added. One sound added was ABS sound recorded from the automobile currently in SIM-3 and filtered to remove noise. This sound is then played in different speakers to simulate sound from different wheels.

Another sound that was added was a crash sound since when testing the scenario before the study test drivers did not understand what happened. This sound was recorded during a playback of a crash test and then modified to fit the scenario, i.e., the crash in the scenario happens faster and the driver drives away from the crash site quite fast, thus the sound should fade away.

6.2 Analyzing data from the simulation study

Here a presentation of how data acquired from the study has been processed and evaluated is made. One thing to remember is that the test drivers used in the study were friends and other volunteers participating freely and might therefore not be a significant test group, thus the results should be interpreted with caution.

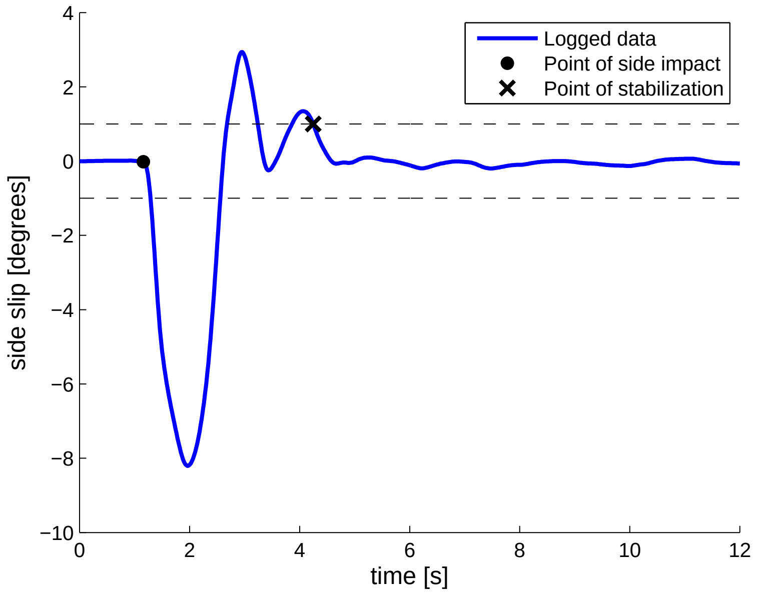

Figure 6.3. The slip plotted in time with the limits of one degree taken from a test driver during the study.

6.2.1 Methods to analyze data

When analyzing data there are several ways to do it. The approach here is that a basic analyzing method which presents the performance in a clear way is wanted. The main component to look at has been the slip angle, and we also look at the amount of drivers loosing control of the automobile.

Using the slip angle as a time to stabilize measurement

When driving straight, the slip should be zero. Since the scenario occurs on a straight road, the driver strives to regain control and continue to drive straight, thus the slip angle will be controlled towards zero by the driver. When the push affects the driver, the slip will start to deviate largely from zero, thus we use this as a measure to see how fast the driver regains control of the automobile. The driver is to have regained control when the slip angle goes below a threshold value and does not exceed this threshold again. As a limit in this study, a slip angle of 1 degree was chosen. According to [19] when driving on ice, the steerability is lost at slip angles of 2 degrees for normal drivers, and since we drive on snow this value will be higher. Therefore we assume that a normal driver that maintains a slip angle below a 1 degree threshold will be considered to have control over the automobile. An illustration of how this time is measured is shown in Figure 6.3.

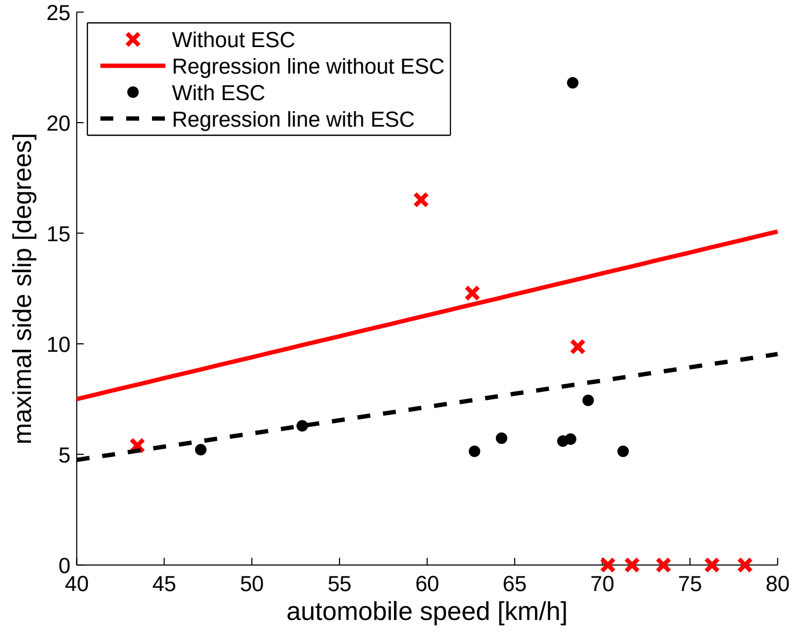

Figure 6.4. Data acquired from part one of the scenario. Drivers that lost control is marked with a maximal side slip at zero.

Using the maximal value of the slip angle

Another thing to measure is the maximum slip angle because it is easy to extract it from data while still providing a lot of information. In [15] they use a limit on the slip angle such that if the maximal slip angle exceeds this limit it will count as a loss of control, thus the maximal slip angle should be below this limit and preferably as low as possible.

6.2.2 Results from part one of the scenario

To reduce the amount of data to present, we mainly look at the slip angles, the automobile initial speed and if the driver looses control or not. These results are presented in Figure 6.4 where a linear regression is also applied. In this figure, test drivers that had an ESC system active are presented with an x and those with the ESC system inactive are presented with a dot. If a test diver lost control of the automobile this is presented with a maximal slip at zero. We see that every test driver with the ESC system active managed to maintain control while five test drivers with the ESC system inactive did not manage to maintain control. Data acquired where drivers have lost control of the automobile has not been used when calculating the regression line.

As seen in this data, drivers without the ESC system active were driving faster (an average speed of 67.1 km/h) than drivers with the ESC system active (an average speed of 63.5 km/h). Since the drivers have not been aware whether the ESC system was active or not, this difference is due to different drivers driving and reacting differently to the scenario.

6.2.3 Results from part two of the scenario

When analyzing data from part two we will look at two things. First, there were drivers losing control of the automobile both with the ESC system active (approximately 2 percent) and with the ESC system inactive (approximately 45 percent). Secondly, we look at the time it took to stabilize the slip angle to a value under 1 degree. Since there were a lot of drivers losing control the time to stabilize is counted from the best time, i.e., the shortest time, with and without the ESC system. When looking at this data, it was seen that every test driver had a faster stabilization time with the ESC active, thus the question "How much better is it with the ESC system active?" arise. Since there were test drivers that did not manage to maintain control without the ESC system active during any try, these test drivers were discarded due to difficulties in calculating the benefit. One approach could have been to count a loss of control as an infinite stabilization time which gives these discarded drivers a 100 percent benefit, but this is not done. Between all the other test drivers the comparison made has been:

$$\text{Percentage benefit: } \eta = \frac{t_{WoE} - t_{WE}}{t_{WoE}} \tag{6.7}$$

Where t_{WoE} is the stabilization time without the ESC system active and t_{WE} is the stabilization time with the ESC system active. A histogram over the results is seen in Figure 6.5 and we approximate that this data is from a normal distribution. This approximation will be better as the number of test drivers increase, but since we do not have that many test drivers this approximation is uncertain. To reflect this uncertainty we use a t-distribution to get a larger confidence interval (approximately 2 percent) than we would if we would have used a normal distribution. The equation used to calculate this interval is then:

$$I = [\eta_{avg} - t_{\alpha/2}(n-1)\frac{s}{\sqrt{n}}, \eta_{avg} + t_{\alpha/2}(n-1)\frac{s}{\sqrt{n}}] \tag{6.8}$$

where $1 - \alpha$ is the confidence limit used for a two sided confidence interval, η_{avg} is the mean value of all the percentage benefits η, n is the number of samples i.e. the number of test drivers, $t_{\alpha/2}(n-1)$ is a tabulated value from a t-distribution and s is the standard deviation. I is the resulting interval. For a more in depth explanation on t-distributions see for example [3].

This gives us that the expected value is somewhere between 40 to 62 percent with a 95 percent certainty, thus an improvement of 40 to 62 percent in the time it takes to stabilize the automobile could be expected when activating an ESC system.

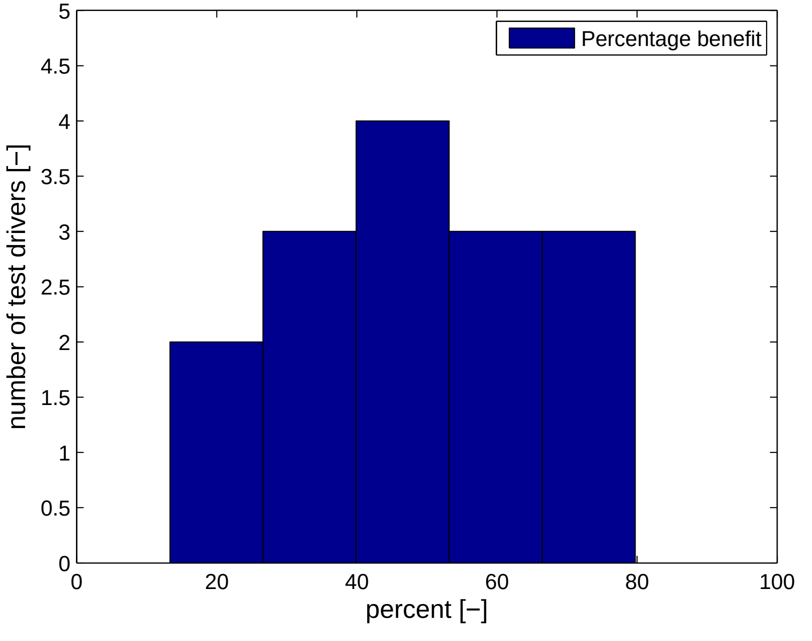

Figure 6.5. A histogram over the percentage benefits from the test drivers during the second part of the study.

Question	Average answer
Can you describe the course of events?	4.4
Were you prepared that something unexpected would occur?	3.0
Did you drive as you normally do?	3.7
Do you think the scenario was realistic?	4.1
Do you believe that you had help from the ESC system?	4.6
Do you feel sick after driving?	1.7
Do you see a benefit with an ESC system in this situation?	4.9

Table 6.1. Average answers from the question form filled in by the test drivers.

6.2.4 Results from the forms

The question form filled in by test drivers contained questions with five boxes for the test driver to rate its answer. To evaluate the answers from these forms a scale from 1 to 5 has been used to rate these boxes, where 1 is not at all and a 5 is completely. Then the average from the questions was calculated and these results are presented in Table 6.1. Note that not all questions from the form are presented here, due to that one question required the test driver to have experienced an ESC intervention in a production automobile and another question was a yes or no question. Since there were so few having experienced an ESC intervention the answer to this question will not be presented, and the yes or no question will not either be presented since test drivers usually guessed. The question ”Can you describe the course of events?” was treated a little special. Here the test driver was asked to describe what happened and then the operator evaluated how well the test driver's version corresponded with what happened in the study.

Chapter 7

Conclusions

From the validation and the results conclusions have been made, these conclusions are here presented in parts. A short outlook on future work is also presented.

7.1 The ESC system

As seen during the validation of the implemented ESC system the system works as intended, thus being realistic. Test drivers testing the system before and during the study have confirmed that they think that the feeling in the simulator is realistic. One thing to remember here is that the ESC system is a safety system that will usually not be active. Of those that have an ESC system installed in their car, the system has luckily only on rare occasions or never been activated, thus one could question the experience from the test drivers. Since no data on how an actual ESC system performs has been used to validate the implemented system, these comments from test drivers has been highly valued when deciding that the system feels realistic enough.

7.2 The study

Since the scenario is divided into an unaware part and a part where the driver is aware of that something will happen, reflections from both parts will be made and then a summarization of these reflections is made.

It is desired that all the test drivers drive as they usually would do and that they do not suspect that anything unexpected, as a side impact, will occur.

7.2.1 Reflections from part one

Begin with a look at the answers from the form. Here we see that most of the drivers expect something to happen and as stated from a few of the test drivers, they said that they expected a moose to suddenly run onto the road. These suspicions lead to test drivers driving slower and reacting faster than they normally do, which has been noted by the operator observing the test drivers during the scenario. But while drivers suspected that something probably would happen they usually did not expect to be hit by another car. Thus, the conclusion is that the scenario worked well but some improvements can be made.

As is seen from the data acquired from part one, shown in Figure 6.4, it is difficult to make any accurate conclusion due to the fact that there is a difference in speed between the test drivers. This is because the speed of the automobile will influence the probability to maintain control of the automobile, and how test drivers with the ESC system active would have managed the side crash if driving faster is not known. If we look at the linear regression we can draw the conclusion that if drivers with the ESC system active behave approximately as the regression line predicts, there will be a benefit from the system according to the maximal slip angle, but there are large individual deviations between drivers and the relation between speed and the maximal slip angle is most certainly not linear. From these reflections we can summarize that there appears to be a benefit but more testing is needed, thus the final conclusion from part one of the scenario is that the scenario worked well and gives an indication of that an ESC system helps the driver in this situation.

7.2.2 Reflections from part two

In part two when the test driver is prepared for the side impact, any effects from surprising the driver are gone, thus the focus has been on how much the system helps the driver when a side impact occurs. Since we do not need to surprise the test driver, the side impact can be repeated several times. The reason that the side impact is only repeated 3 times with the ESC system active and 3 times with the ESC system inactive is to avoid motion sickness. This means that the results are more accurate than in part one of the scenario due to the increase in amount of data acquired. This makes it easier to make a statistically significant conclusion on this data, that the ESC system clearly helps the driver in reducing the stabilization time by 40 to 62 percent. To remember is also that there were a lot of test drivers that lost control of the automobile (45 percent without an ESC system and 2 percent with an ESC system) also indicating a great benefit from the ESC system. To summarize, the ESC system definitely helps the driver to regain control of the automobile easier thus preventing loss of control.

7.2.3 Final conclusions

As shown, the ESC system definitely helps the driver when the driver knows about the side impact, but when the driver is unaware the conclusion that the ESC system helps is a lot more unsure even though there are indications that the ESC system also helps in this situation. If the tests were to be redone, more test drivers would be required to get more statistically significant results during the parts of the scenario where it is required that the driver is unaware that something will happen, and the scenario could need some optimization to get drivers more comfortable and less suspicious of that something will happen.

7.2.4 Future work

There are a lot of things that would be interesting to look at in the future, we will state a few. We start with mentioning some improvements that can be made to the implemented ESC system and the created scenario:

- The control algorithm could be improved using a more advanced approach.
- The brake dynamics could be more realistically modeled.
- The brake logics could be improved to in a sophisticated way brake more than one wheel.
- The interaction between the engine intervention and braking wheels can be improved.
- Install a production ESC system in the simulator.
- A more realistic crash model could be implemented.

There are also other tests that can be done in the simulator which are closely related to this work:

- Implement an ESC system into a heavy vehicle.
- Implement active steering which could be tested separately or in conjunction with an ESC system.
- Studies when an ESC system malfunctions could be made.
- A study with an optimal ESC system could be made since the friction and automobile parameters are known at every instance in time in the simulator.

Appendix A

Lateral acceleration

The linearized single-track model, which is used in this thesis, is only valid for a lateral acceleration below 0.4 g when compared to a real automobile, see [9]. We would like to validate that the similar situation occurs in the SIM-3 environment with the current vehicle model and the linearized single-track model. To test this an increasing steering wheel test is done.

A.1 Increasing steering wheel test

This test proceeds as first the automobile is accelerated to a preset speed, which in this case will be 80 km/h. Then the steer wheel angle is slowly increased, and in this test the steer wheel starts to turn right. During this turn we log the reference values and the automobile lateral acceleration, this data is seen in Figure A.1 and Figure A.2.

Here we see that we have a good model up to the time around 50 s, thus the lateral acceleration here would be the point where the model stops to provide accurate result. The lateral acceleration at the time 50 s is approximately 0.44 g which is fairly close to 0.4 g specified in literature, thus the setup in the simulator could be seen as a realistic setup.

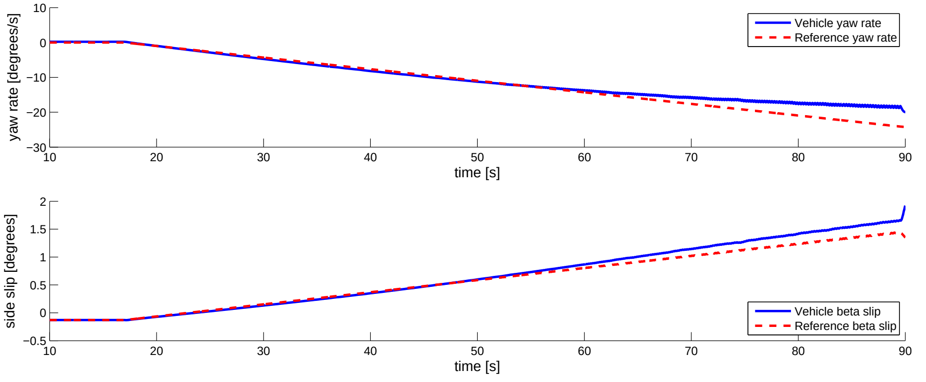

Figure A.1. Calculated reference values and ”measured” data during an increasing steer wheel angle maneuver.

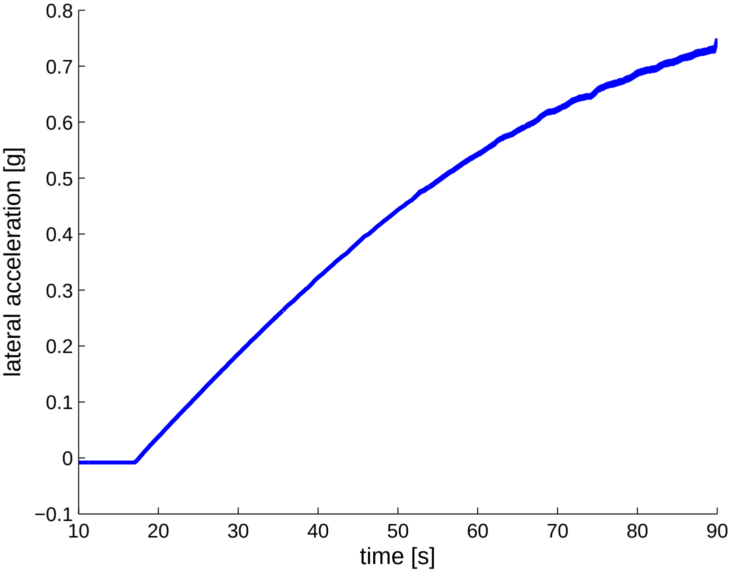

Figure A.2. Lateral acceleration from an increasing steering wheel angle test on a high friction surface.

Appendix B

Sine with a dwell

The maneuver called the 0.7 Hz sine with a dwell is described by NHTSA in [14] and is an oversteer maneuver recommended by NHTSA when evaluating an ESC system. The maneuver is described below. When the maneuver is done there are criterions that have to be met and these criterions will also be described below.

B.1 0.7 Hz sine with a dwell

This maneuver consists of a modified sinusoidal steering input at 0.7 Hz. There is a possibility to use different frequencies but the 0.7 Hz has proven to be effective and is the one recommended, thus the one used here. The amplitude during each test is increased from an initial value until a termination criterion, and the maneuver with an amplitude of 180 degrees is shown in Figure B.1. When the tests starts, two series are done, one where the steering starts to the left and one where the steering starts to the right. In every test the steering is initiated at 80 km/h on a high friction surface. The rate at which the amplitude increases and the initial steering are parameters that has to be chosen and also a termination criterion has to be chosen.

B.2 Lateral stability criteria

To assure us that the ESC system stabilizes the automobile fast enough there are criterions that expresses the yaw velocity at a specific moment in time to a peak value. These criterions are:

$$\frac{\dot{\Psi}(t_0 + 1.00)}{\dot{\Psi}_{Peak}} \leq 0.35 \tag{B.1a}$$

$$\frac{\dot{\Psi}(t_0 + 1.75)}{\dot{\Psi}_{Peak}} \leq 0.20 \tag{B.1b}$$

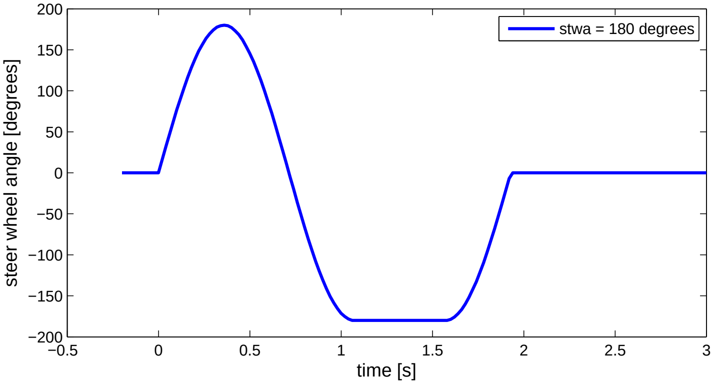

Figure B.1. A 0.7 Hz sine with a dwell maneuver with a maximum steer wheel input at 180 degrees.

Here t_0 is the time when the steering is completed and $\dot{\Psi}_{Peak}$ is the maximum yaw rate which is usually reached in the beginning of the dwell in the maneuver. NHTSA states that if a automobile fulfills these criterions the probability of a spinout would be less than 5 percent with given steering input, see [14].

B.3 Responsiveness criterion

In addition to the lateral criterions there is a responsiveness criterion to assure that the automobile will at least move 1.83 m sideways after 1.07 s, which in a real situation is critical for avoiding potential danger. The 1.07 s is because that is when the dwell starts and is an easily recognized point in time. Proposed measure is to measure the lateral acceleration and then integrate it twice to get the lateral position, this will be unnecessary since we in the simulation environment exactly knows the position of the automobile at all times making measuring unnecessary.

Appendix C

Forms used during the study

When a test driver arrives, the test driver is told to drive normal and if there are any problem he or she should speak out loud since the operator have radio contact with the test driver, thus the test driver will not see any of the forms before part one of the scenario.

C.1 Question form to test driver

After part one of the scenario the operator asks questions to the test driver and the answers are written down on the form by the operator. When done, part two continues and after part two there are a few more questions, which are done in the same manner as the questions after part one. After these questions are finished, the test driver is let out from the simulator and is asked to finish the question form. The reason to ask questions when the driver is in the simulator is to get the feedback while the test driver has it fresh in memory. The question form can be seen in Figure C.1.

C.2 The operator notes form

During the scenario, the operator will also take notes and make judgements on how the test driver appears to be driving. The purpose here is mainly to see that the real time criteria is met, that the test driver appears to drive normal and that the test driver do not feel sick. On this form there are also a few notes to keep the operator from forgetting important things. This form can be seen in Figure C.2.

Testförare nr:____

Frågeformulär

Allmän information

Hur länge har Du haft körkort? _______ år

Hur mycket kör Du om året? ________ mil

Vilka körkortsbehörigheter har Du? ____________ (tex B och C)

Äger Du en bil med ett ESC system? ☐ Ja ☐ Nej

Frågor efter del 1

	Inte alls				Helt
Kan Du beskriva händelseförloppet?	☐	☐	☐	☐	☐
Var Du beredd på att något oväntat skulle inträffa?	☐	☐	☐	☐	☐
Körde Du som Du normalt brukar?	☐	☐	☐	☐	☐
Tror Du att systemet var av eller på?	☐				☐
Tycker Du att det var ett realistiskt scenario?	☐	☐	☐	☐	☐

Frågor efter del 2

	Inte alls				Helt
Tycker Du att Du hade hjälp av systemet?	☐	☐	☐	☐	☐
Om Du har upplevt ett ESC ingrepp, är känslan i simulatorn realistisk?	☐	☐	☐	☐	☐

Några fler allmänna frågor

	Inte alls				Helt
Mår Du illa efter att ha kört?	☐	☐	☐	☐	☐
Ser Du en nytta av ett ESC system i denna situation?	☐	☐	☐	☐	☐

Får vi använda inspelat material för att visa?

____

Övriga synpunkter:

____

Tack för Din medverkan!

Figure C.1. The question form filled in by every test driver.

Testförare nr:____

Kom ihåg noteringar

Innan scenariot drar igång

- Kör som vanligt.
- Om det är något så säg till, jag ser dig hela tiden.
- Det är manuell växellåda.

Observationer till del 1

	Inte alls				Helt
Körde testpersonen normalt på vägen?	☐	☐	☐	☐	☐
Ser testpersonen ut att må bra ut?	☐	☐	☐	☐	☐
Körde testpersonen med en konstant hastighet?	☐	☐	☐	☐	☐
Körde personen ur?	☐	☐	☐	☐	☐
Klarade simuleringen realtidskraven?	☐	☐	☐	☐	☐
Var ESC systemet aktiverat?	☐				☐

- Glöm inte att säga till att om testpersonen börjar må dåligt så måste han/hon säga till.
- Det är helt OK att ta en liten paus.
- Förklara även syftet med testet.

Observationer till del 2

	Inte alls				Helt
Ser testpersonen ut att må bra?	☐	☐	☐	☐	☐

Övrigt

- Förklara att det finns plausibilitetskontroller som stänger av systemet i ett liknande fall.

Övriga tankar:

____

____

____

Figure C.2. The operator notes form used by the operator for each test driver.

Appendix D

Nomenclature

D.1 Automobile parameters

$BRT_{FL,FR,RL,RR}$	linearized brake to torque factor
c_F	front tire cornering stiffness
c_R	rear tire cornering stiffness
i_S	transmission ratio between the steering wheel angle and wheel angle
J_Z	moment of inertia about vertical axis
l	distance from rear to front axle
l_F	distance from automobile CoG to front axle
l_R	distance from automobile CoG to rear axle
m_{CoG}	automobile mass
P_n	current brake pressure
r	vector from automobile CoG to a wheel
r_0	original wheel radius
v_{CoG}	automobile speed at the CoG
v_{ch}	characteristic speed of the automobile
$v_{ch,\epsilon}$	characteristic speed of the automobile with a mass error
v_X	automobile longitudinal speed
v_Y	automobile lateral speed
β	automobile body side slip angle
β_{ref}	automobile body side slip angle reference from the ESC system
δ_S	steering wheel turn angle
δ_W	wheel turn angle
ϵ_m	percentage error in automobile mass
$\dot{\Psi}$	automobile yaw rate
$\dot{\Psi}_{ref}$	automobile yaw rate reference from the ESC system
$\dot{\Psi}_{ref,\epsilon}$	yaw rate of an automobile with a mass error

D.2 Control parameters

$e_{high,limit}$	limit where the ESC system activates if inactive
$e_{low,limit}$	limit where the ESC system inactivates if active
e_n	control error
F_{des}	desired force at a wheel
K_p	control parameter adjusting the proportional part in a PD controller
P_{des}	desired pressure at a wheel
T_d	control parameter adjusting the derivative part in a PD controller
T_s	sample period time
ξ	control parameter to adjust side slip influence on the control error
τ_s	time constant

D.3 Side impact parameters

e	coefficient of restitution
F_{push}	maximal side impact force done to the automobile
I	impulse
p	linear momentum
t	time
v	speed
ω	angular frequency

D.4 Statistical parameters

n	number of samples
s	standard deviation
t_{WoE}	stabilization time without an ESC system
t_{WE}	stabilization time with an ESC system
$t_{\alpha/2}(n-1)$	tabulated value from a t-distribution
α	$1-\alpha$ is the confidence limit of a two sided confidence interval
η	percentage benefit for a test driver

D.5 Abbreviations

ABS	Anti-lock braking system, Antiblockiersystem
BRT	linearized brake to torque factor
CoG	Center of Gravity
ESC	Electronic Stability Control
SIM-3	Simulator III at VTI
stwa	steer wheel angle
VTI	Swedish Road and Transport Research Institute

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