CHALMERS

Post Impact Stability Control Verification

in driving simulator

Master's thesis in System, Control and Mechatronics

PONTUS PETERSSON

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Abstract

During the thesis an implementation and verification of the Post Impact Stability Control (PISC) function was done in a driving simulator. The aim of the function is to avoid, or at least mitigate, secondary collisions by minimising the lateral deviation of the vehicle after the initial impact in a multiple-event accident.

The PISC function was developed and tested offline for debugging and tuning purposes as well as to serve as a guideline for the simulator tests. The results were as expected.

The PISC function was also tested in the Chalmers S2 simulator in a study where four different tests were ran, where a set of unprepared test drivers were used in order to evaluate the benefits of the function and to analyse the reaction of the drivers and their interaction with the function.

It was found that the PISC function is beneficial in most situations however a more sophisticated settling controller should be implemented to mitigate some of the undesired effects.

Keywords: Post Impact Stability Control, function evaluation, driving simulator, multiple-event accidents, MEA, active safety, Hardware In Loop, HIL

Preface

This study was carried out for the Division of Vehicle Dynamics at Chalmers University of Technology, in cooperation with Volvo Car Corporation, by two students from the Master program *System, Control and Mechatronics* during the spring of 2013.

The theoretical parts and the model development parts were carried out in the Vehicle Dynamics division in the Applied Mechanical department while the experiments and the simulator model development were done in the Vehicle Dynamics lab.

The present work is based on the previous studies on Post Impact Stability Control made by Derong Yang from Chalmers University of Technology.

Acknowledgements

We would like to thank our supervisors Derong Yang and Bengt Jacobson for their invaluable help and advices during the development of the thesis.

We would also like to thanks Fredrik Bruzelius at VTI for the advice and help while working on the model.

A special thanks to Josef Nilsson for pointers regarding the simulator and to Artem Kusachov and Faouzi Al Mouatamid for the help and input with simulator quirks and tricks.

Contents

1 Introduction

This report describes the implementation of a validation method for the Post Impact Stability Control (PISC) function in a driving simulator in order to evaluate its efficiency. The PISC function aims to reduce the lateral deviation (henceforth referred to as Y_{max}) in order to reduce the risk, or at least mitigate the effect, of a secondary collisions. For the function to work efficiently Y_{max} should be reduced but the collision risk and overall severity after the first impact should be reduced, hence the speeds, side slip angle, yaw angle and yaw rate are also monitored to ensure good functioning of the PISC function.

This chapter will also describe the goals and background of this thesis as well as give an overview of the literature used as support.

1.1 Master Thesis Goal

The thesis work aims at developing a method for evaluation of the efficiency of the PISC function and to evaluate one version of the PISC function. It is a prerequisite that a driving simulator should be used in order to avoid driver model induced errors. Since a simulator induces realistic driving and collision feel to the driver it will cause a realistic reaction by the driver.

To properly evaluate the method a set of clinics will be performed, with unprepared drivers to reliably evaluate real drivers' reactions to impacts and to the intervention of the PISC function.

1.2 Background

When a vehicle impact accident occurs it is not uncommon that the driver of the primary vehicle loses control of the vehicle, due to violent car displacement, high lateral velocities, high yaw rate and side slip or to losing consciousness. In a significant portion of these accidents the primary vehicle then is exposed to a secondary impact caused by lack of control. In this secondary impact, whether with a stationary object or another vehicle, the passengers are much more exposed since by then any airbags will probably already have been deployed and any deformations zones might be compromised. All these factors will most likely lead to further or more severe injuries.

By incorporating a safety feature that automatically takes control of the vehicle and strives to regain vehicle course stability and to as soon as possible bring the vehicle to a halt after an impact the risk of secondary events would be reduced significantly. The PISC function is designed to do exactly that.

By creating a validation method using a vehicle simulator the function could be evaluated at minor costs and could more easily be made appealing to vehicle manufacturers.

1.3 Literature Review

In this section the most important publications used in the literature study will be presented.

1.3.1 Post impact braking verification in motion platform simulator (Kusachov & Al Mouatamid, 2012)

This Master Thesis was developed at Chalmers in 2012. The goal was verification through a motion platform simulator of a Post Impact Breaking (PIB) function using a set of experiments with prepared and unprepared drivers in both the Chalmers S2 simulator and the VTI IV simulator. This thesis was used as the main support of this work since it uses the same methods, equipment and setup but evaluating a different function.

1.3.2 A Vehicle Dynamics Model for Driving Simulators (Fernández, 2012)

This Master thesis was developed at Chalmers for VTI in 2012. The goal of the work was to develop a Modelica based model to implement in the driving simulator *SimIV* at VTI in Göteborg. The vehicle model produced by this thesis kept being developed and the subsequent iterations of the model were to be implemented in the

Chalmers S2 simulator as part of this thesis, however due to the constant development of the model a stable version could not be implemented.

1.3.3 Vehicle Stability Control for Roadside Departure Incidents by Steering Wheel Torque Superposition (Benito & Nilsson, 2006)

This Master Thesis was developed at Chalmers in 2006. The goal was to investigate the feasibility of a system to help the driver maintain control of the car through active superposition of torque on the steering wheel using the electric power steering. Part of the project was to develop a model compatible with the Chalmers S2 driving simulator. The model is used to implement in the Chalmers simulator with the added PISC function.

1.3.4 Quasi-Linear Optimal Path Controller Applied to Post Impact Vehicle Dynamics(Yang et al., 2012)

This scientific paper is at the core of the thesis work since it describes the PISC function that was implemented as well as the motivations for the development of such a function.

The thesis was prompted as a way to verify within a safe and controlled environment the validity of the results obtained by D.Yang in this paper with the inclusion of a real driver.

1.3.5 Handwheel Force Feedback (Switkes et al., 2006)

This article describes a method for combining force feedback in the steering wheel with a lane keeping assistance controller to help keep a speeding vehicle in the lane in order to avoid unintended lane departure.

The article describes modelling of the vehicle and controller and also presents a stability analysis of the system which is critical when dealing with active steering interventions.

2 Vehicle Model

The initial idea was to use the Modelica developed by J.Fernandéz at VTI ([Fer12]). However this was not possible due to some compatibility issues with the simulator, therefore for this thesis work a simulink based XC90 vehicle model was used and implemented both in offline and online simulations.

The specifications and implementation of both the online and the offline models are discussed in the following sections.

2.1 Volvo XC90 offline model

The Volvo XC90 model (from here on referred as XC90) was inherited from the work of Kusachov & Al Mouatamid [KM12], and was based on the work of Benito & Nilsson [BN06]. The top level of the model can be seen in figure 2.1

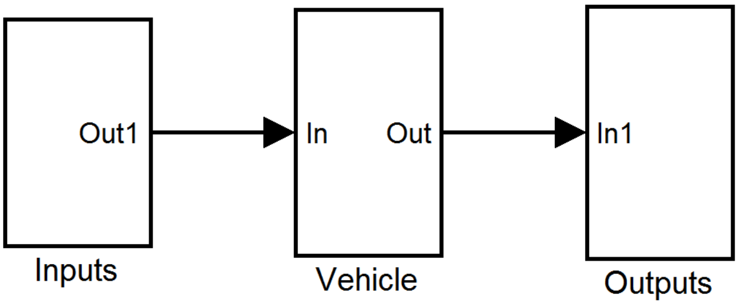

Figure 2.1: *Top most level of the offline vehicle model*

The model was implemented entirely in Simulink using 6 blocks, one for each component of the vehicle; chassis, wheels, steering, brakes, powertrain and vehicle control. This made the model relatively intuitive and quite easy to navigate. The Simulink model also included several Matlab scripts for initialisation of the parameters. The vehicle block in both the offline and the online model are identical and can be seen in figure 2.2.

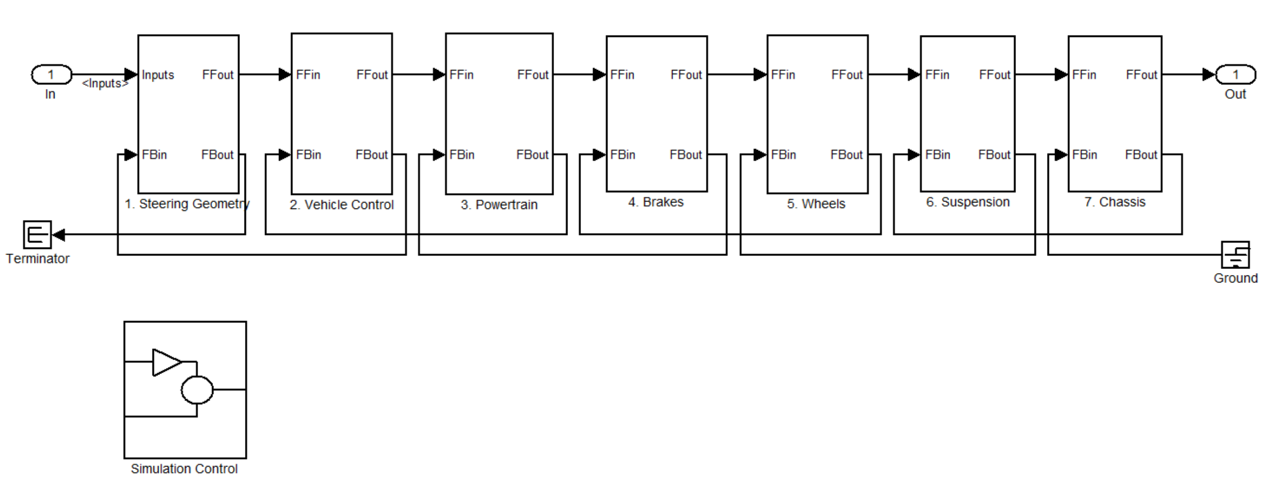

Figure 2.2: *Layout of the vehicle subsystem, in fig 2.1 and 2.3*

The model was modified to accommodate the PISC function in the vehicle control block and for the steering torque and braking torque requests to be able to influence the vehicle dynamics.

Since the XC90 model had been used previously to verify a Post-Impact Braking function the required set up for impacts was already implemented and just had to be verified.

The offline model was set up to verify the response of the car and if the results for the PISC effect were as predicted. The offline model results were also compared with the online model results for consistency checking.

2.2 Volvo XC90 online model

The online model used the same vehicle model setup but had a different shell since the inputs and outputs required and provided by the simulator were different from the ones in Simulink, the top most level of the online vehicle model can be seen in figure 2.3

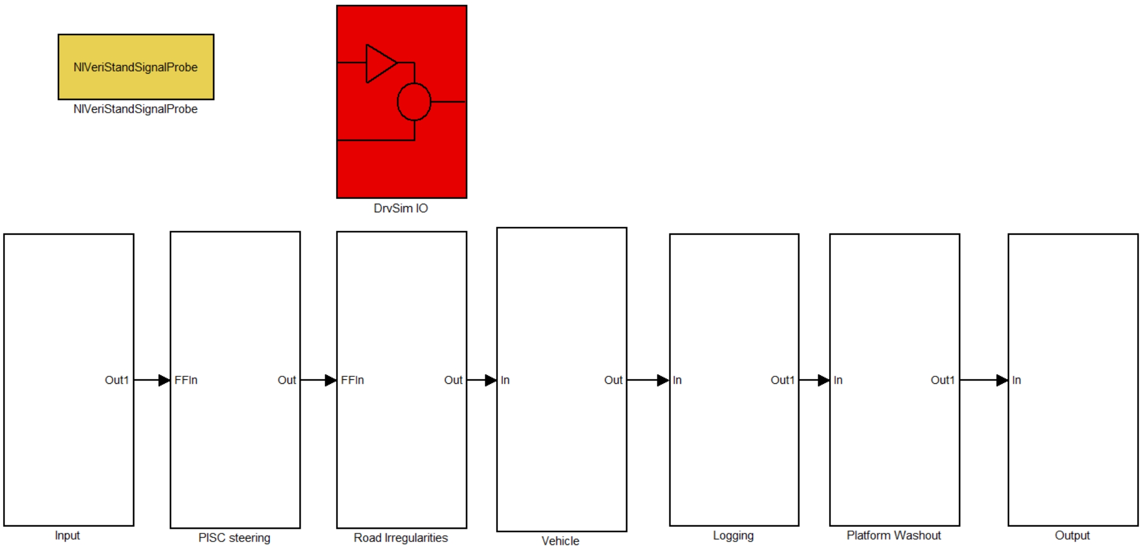

Figure 2.3: *Top most level of the online vehicle model*

The differences between the two models are due to the connections needed between the simulink model and the real time machine and also due to the conversions that have to be made so that the values outputted from the vehicle model are consistent with the inputs of the simulator. The interface with the real time machine is done through the DrvSim I/O block (red) that stores the inputs and output connections and the NI Veristand Signal Probe block (yellow) that creates a library to support the interface.

Due to MatLab related issues an extra block had to be added to the model, the PISC steering block. This block is responsible for the arbitration between the driver's steering and the function's steering request.

In order to have a more easy to control simulation all the control functions were made to be activated from the simulator's control panel. The impact definition (position, angle, amplitude) and the triggering could also be controlled from the simulators control panel.

The simulator used was the Chalmers S2 simulator which is described in further detail in the chapter Simulator platform.

2.3 Impact model

The whole project depends also on the correct definition of the impact. The required inputs were added in the thesis by Kusachov & Al Mouatamid [KM12] and verified in this thesis. The setup is depicted in figure 2.4.

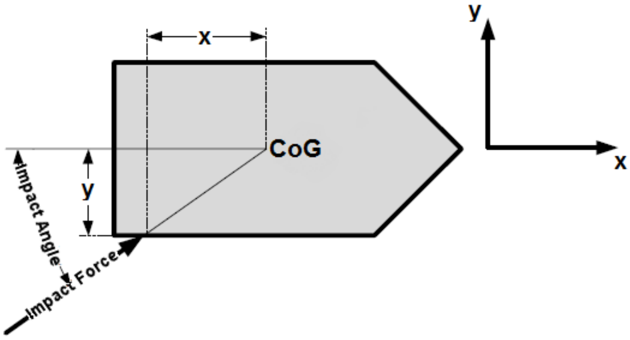

Figure 2.4: *Impact Definition*

The impact model described in figure 2.4 is parametrized as:

- X - Longitudinal position of impact point, forward of CoG is positive
- Y - Lateral position of impact point, to the left is positive
- Impact angle - Angle between impact and longitudinal centre-line of the vehicle, counterclockwise is positive
- Impact force - External force applied through impact, vector entity

3 PISC function

The PISC function was developed during the PhD thesis of Derong Yang (c.f. [Yan+11] and [Yan+12]). The function tries to minimise the maximum lateral deviation by braking and suggesting a steering angle to the driver.

3.1 Setup

The control algorithm was developed as a Simulink block function supported by a Matlab initialisation script. However it had no triggering algorithm to enable and disable the function and hand-back the control to the driver. The contents the the simulink block can be seen in appendix A. PISC function.

When activated the function calculates the wheel angle and braking torque required to minimise the lateral deviation based on the lateral speed, the longitudinal speed, the lateral position, the yaw rate, the yaw angle, the vertical load and the road friction coefficient.

3.2 Triggering

The triggering algorithm was designed in Simulink and decides if it should engage the PISC function based on the speed of the vehicle, the impact detection and driver inputs. The triggering activates the PISC function immediately after the impact has ended.

The triggering was developed for use in the simulator. In a real world application the triggering would be based mainly on airbag sensor signals.

The deactivation of PISC is done right after the maximum lateral deviation is reached and after the PISC function is disabled the steering control is returned to the driver and the PIB function is responsible for the brake actuation.

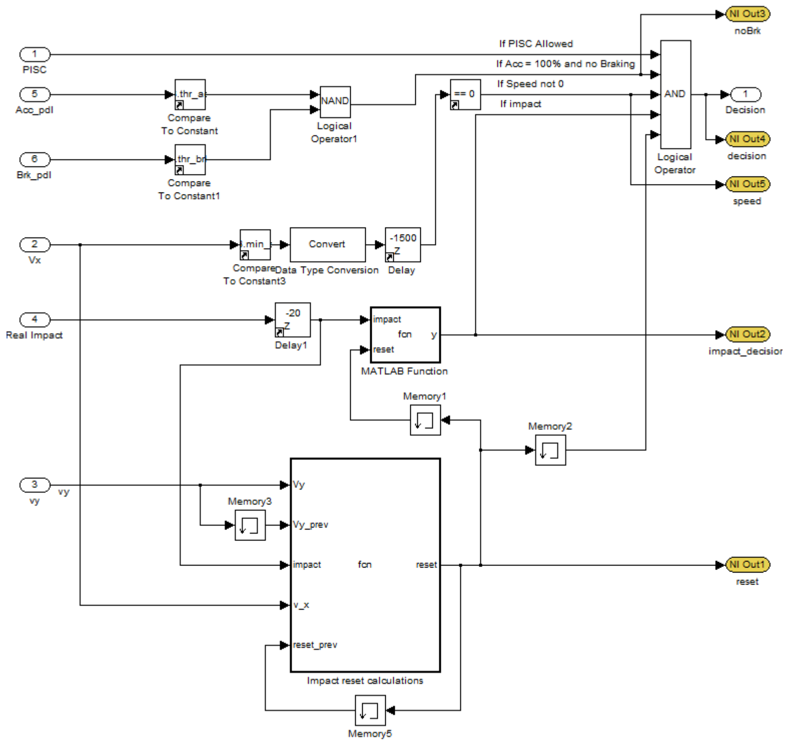

Figure 3.1: *Simulink Decision Block*

The decision block in figure 3.1 outputs 1 or 0 depending on the inputs and it determines if the PISC should overtake the control from the driver or not. If all the following inputs are 1 then the PISC is active:

- PISC - if the PISC is allowed (1 for on, 0 for off), so that the usage of the PISC can be determined before testing
- Pedal position - if the driver not at full throttle (PISC can be overwritten if driver accelerates fully)
- Longitudinal speed - if the car is not standing still.
- Impact - if an impact is detected
- Disengage - if the vehicle has not yet reached the maximum lateral deviation.

The PISC function calculates the needed steering angle and brake torque needed to minimise the lateral deviation hence it should only be enabled until the car reaches the maximum lateral deviation (Y_{max}). To determine that the global lateral speed is used. If the lateral speed changes sign it means that it crossed 0 and therefore the maximum lateral deviation was reached and the function has to be turned off so that the PIB function can be engaged.

3.3 PISC Function

The PISC function as designed by D.Yang [Yan+12] is a vehicle stability function that minimises the lateral deviation. It calculates the front axle steering angle and the brake force in each individual wheel, to ensure its goal.

3.3.1 Brake arbitration

Superposing the calculated brake torques with the driver's brake input would alter the vehicle response to a point where the calculated torques would likely become invalid or the PISC intervention would be far from the intended one. To counter this potential issue a brake-by-wire implementation was chosen, which overrides the driver's braking input for the duration of PISC intervention. This method is acceptable since we have a brake pedal override mechanism.

Any other active safety systems commonly available in production cars (ABS etc.) are only considered when PISC is not engaged.

3.3.2 Steering arbitration

To incorporate the steering suggestion calculated by PISC a torque arbitration block using a PD-controller was constructed in Simulink that converts the difference between the current steering angle and the one suggested by PISC to a feedback torque that along with the self aligning torque is sent to the steering feedback motor. The block is presented in figure 3.2.

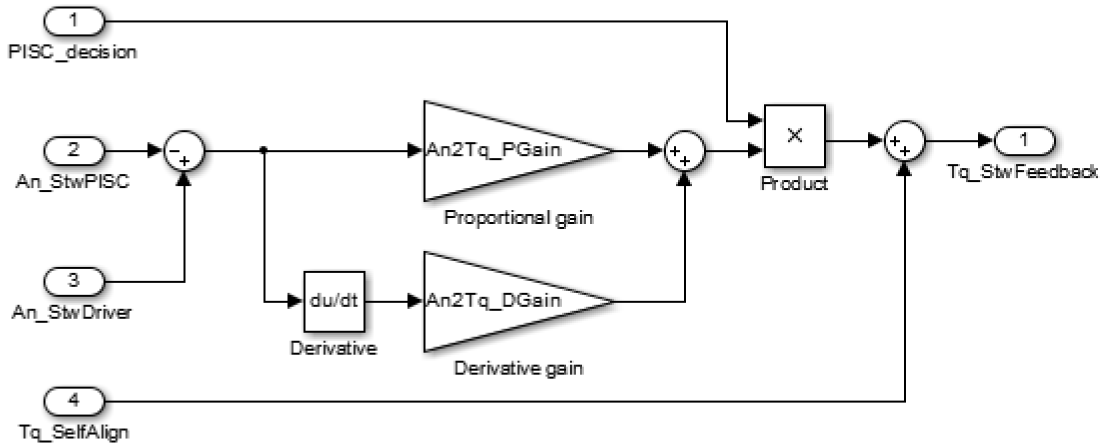

Figure 3.2: *Torque arbitration block*

In figure 3.2 the signal $Tq_{-SelfAlign}$ is the contribution to steering column torque from the self alignment torque after it has been sent through power steering.

In an impact event it is plausible that the driver loses consciousness or for some other reason loses grip of the steering wheel. The system can be tuned so that in such an event the torque feedback makes the steering wheel turn in the desired direction on it's own, to some extent.

The steering wheel angle is at all times what is used by the vehicle model, the calculated PISC steering angle is only used for calculating the steering torque feedback. The calculations are done using a PD-controller with $P_{gain} = 5$ $[Nm/(deg/s)]$ and $D_{gain} = 1$ $[Nm/(deg/s^2)]$.

This setup is tested offline through simulations in the chapter 5.4.3.

A similar torque arbitration has been used in VTI simulator Sim4 to test a Lane Keeping Aid function. It also includes an integration part and utilized the following gains: $P_{gain} = 10$ $[Nm/(deg/s)]$, $I_{gain} = 250$ $[Nm/deg]$, $D_{gain} = 1.5$ $[Nm/(deg/s^2)]$.

Due to the limitations explained in chapter 4.4 a steer-by-wire setup was instead chosen for the clinics, see chapter 6. In that setup the arbitrator switches between outputting the driver and PISC steering, essentially alternating the input to the vehicle model.

3.4 Settling

There is no settling control in its more strict definition. Instead after the PISC has disengaged the PIB function engages and works as a settling function but leaves the driver in charge of the steering.

The PIB function is thoroughly explained in the thesis report *Post impact braking verification in motion platform simulator* [KM12]. Simply put the PIB function requests the maximum braking force possible (limited by the same individual wheel slip control as the ABS) in order to stop the car as fast and as safely as possible.

4 Simulator platform

The simulation platform used was the Chalmers S2 simulator. It is a 6 degrees of freedom platform with a cockpit that consists of the forward part of the driver side of a Volvo V40 with all the required connections. It also includes two screens, one in the front and one in the left rear view mirror.

The whole cockpit module is mounted on a hexapod platform system to provide motion. However the motion platform was not used during this thesis due to some unexpected hardware problems that is explained in further detail in section 4.4.

4.1 Simulator Architecture

The simulator hardware-software-user interface is done by 4 computers that can be seen in figure 4.1 surrounded by dashed lines.

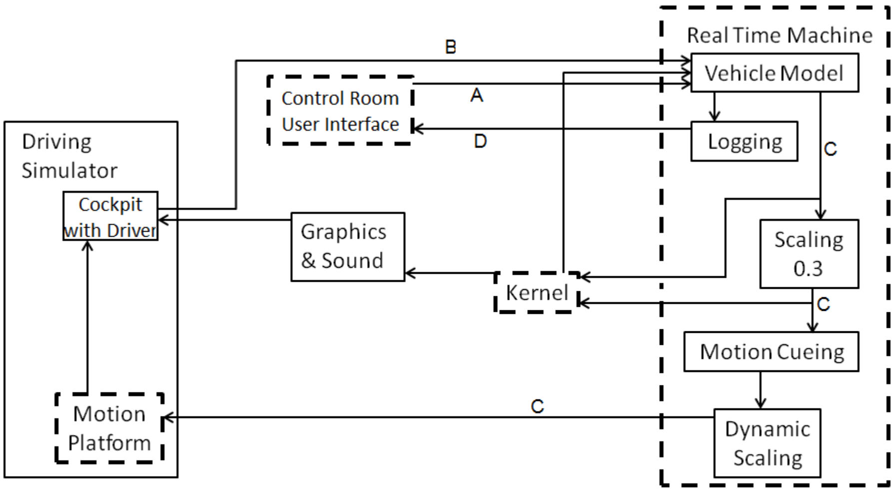

Figure 4.1: *Hardware-Software interaction architecture*

The signals that are routed through the system are:

- A - Impact Characteristics, Control function toggling, Simulation Control
- B - Pedals position, Steering wheel angle
- C - Velocities, Accelerations, Angles, Rates
- D - Dynamic states and flags for logging

The "control room user interface" is responsible for defining the simulation variables and the impact type. The "kernel" runs the driving scenarios and controls all interactions and communication flows between the computers. The car model is sent to the "real-time machine" (NI XPI 1042Q) and all the model outputs are sent to the "kernel" that sends them to the "motion platform" and to the "kernel" responsible for image and sound generation. Additionally there is one computer for backup.

The outputs of the model are all scaled by 0.3 to ensure that the safety limits of the platform are not reached. As a second safe guards a dynamic scaling that can vary between one and zero is used along with the motion cueing and is described in section Motion cueing.

4.2 Hexapod and cockpit

The hexapod is a MOOG Motion System, an electrically powered 6 degrees of freedom system with a flying frame for payload mounting. The motion platform is self-contained and includes its own power systems, servo-controls, safety monitors, etc.

The controlled linear motion of the actuators results in the following six degrees of flying platform motion, represented in figure 4.2:

- Pitch - rotation forward and aft (positive pitch is front up)
- Roll - rotation left and right (positive roll is to the left)
- Yaw - rotation clockwise and counter clockwise (positive yaw is clockwise)
- Heave - vertical motion up and down (positive heave is down)
- Surge - horizontal motion forward and backward (positive surge is forward)
- Lateral - horizontal motion left and right (positive lateral is right)

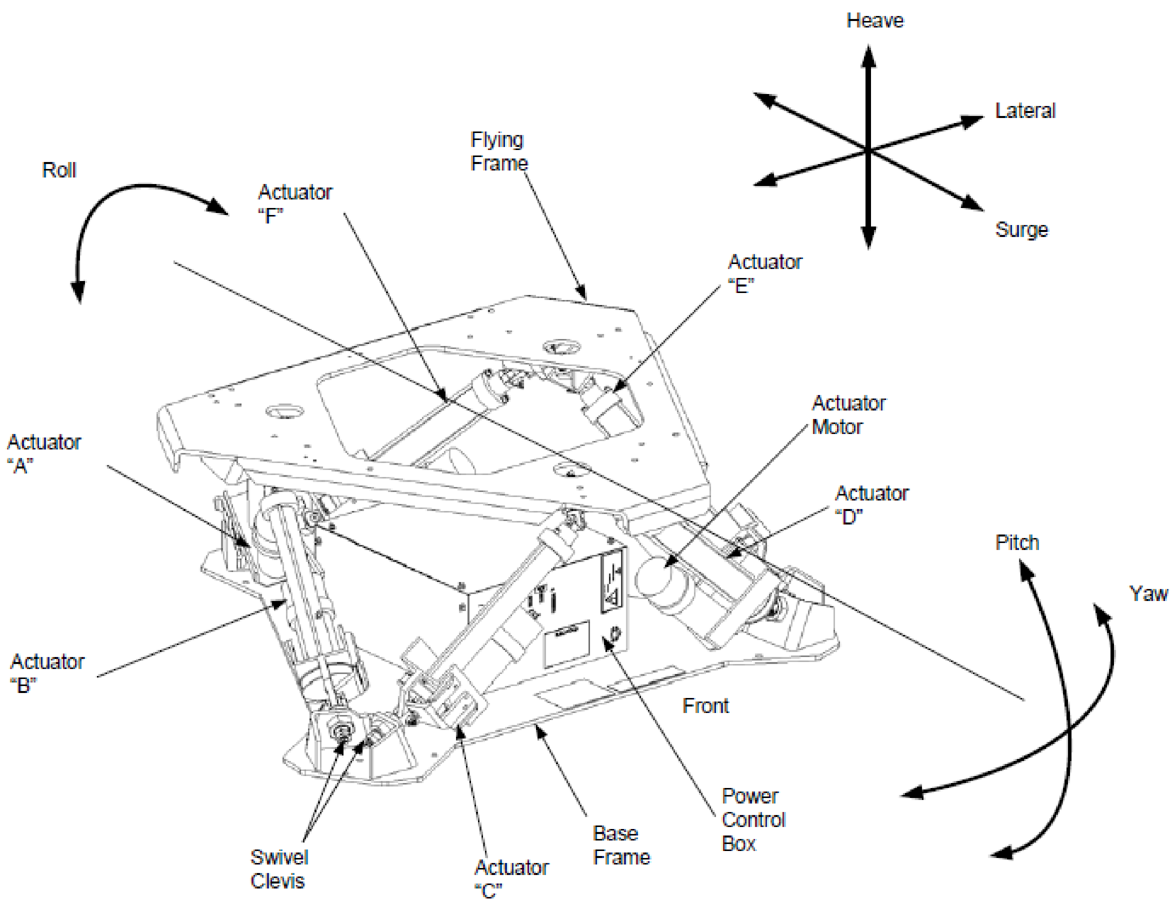

Figure 4.2: *MOOG Motion Platform [Pla]*

The cockpit is an aluminium frame with the driver quarter of a Volvo V40 car body with the control panel, electronics and driving controls. A sound system, a front screen and a rear view mirror display are also included for the visualisation of the driving and sounds for realistic driving sensation.

Since the entirety of the system is inside the frame, the latter is covered with a black tarp in order to prevent light from disturbing the driver.

4.3 Motion cueing

The motion of the platform is controlled by an algorithm that converts the vehicle states (accelerations and rotations) into the motion platform commands (linear and angular displacements). The control strategy uses a model predictive control algorithm based on the bicycle model, a simplified two-wheeled version of a vehicle model. Since there are multiple ways for the platform to simulate each acceleration the controller chooses the option which leave the maximum amount of remaining freedom of motion.

During normal driving conditions the motions of the platform corresponding to the accelerations and rotations outputted by the car model are far below the safety limits of the simulator. In an impact case however the dynamic states may increase beyond the hardware safety limits which would cause the integrated safety systems to trigger an emergency stop in order to prevent any damage coming to the hardware or the driver.

The model includes a dynamic scaling function developed by Kusachov & Al Mouatamid [KM12] that filters the outputs to the platform. The function reads all the signals that are being sent to the motion platform and checks them against its hardware limits, if any of the signals reaches the limit all the signals will be scaled down to preserve the signal proportions and therefore the driving feel. In the case were several of the parameters reach the safety limit at the same time the function will select the scaling coefficient that ensures that all the signals remain safe and that the platform is working at its maximum capacity.

4.4 Hardware issues

During the implementation of the online model issues with both the steering feedback and the motion platform was detected, described each in further detail below.

4.4.1 Steering feedback

During the initial testing of the online model a seemingly complete lack of steering feedback torque was experienced. Eventually a debugging test was run where instead of sending the calculated feedback voltage to the motor a constant voltage close to the hardware limit of the motor was sent. The expectation was that this would trigger a noticeable torque in the steering column but when no reaction was detected the conclusion was that the motor had in some way gotten damaged before this thesis inherited the simulator.

Following the above conclusion the clinics were run without steering feedback (zero requested torque to the electric motor in the simulator cockpit) since repairing/replacing the damaged part wasn't within the scope of this thesis.

4.4.2 Motion platform

During the initial testing of the motion platform some minor vibrations were felt which upon closer inspection were deemed to be caused by lack of proper lubrication of the pistons due to the extended period spent unused. This problem was easily fixed by lubricating each individual piston.

However the vibrations reappeared much more violently this time and the cause of the problem was considered to be environmental. The room in which the simulator is kept in is subject to a lot of movement of people, vehicles and was currently under renovations and no measures were taken to shield the actuators from the dust and dirt that was generated both by the renovations and by the constant opening and closing of the doors that lead straight outside. Since the piston were lubricated not long ago the problem had no clearly visible solution besides taking apart the simulator and cleaning it.

Adding to this problem one of the pistons stopped responding and even after restarting the computers responsible for the signal generation and verifying all the connections to the motion platform the cause of the problem remained unknown and therefore no solution was found.

Due to the the extent of the problems generated in a short time span by the motion platform and those being either unknown or solvable only by extensive disassembling and reassembling of delicate equipment it was decided that the clinics would be done without motion.

5 Offline Simulation

Before implementing the vehicle model with the PISC function in the simulator it had to be implemented in Simulink due to two important factors. On one hand because although the model had been used and verified previously it had to be check for inconsistencies and bugs; on the other because the PISC function itself had to be tested to verify that the results were as expected.

5.1 Verification

The verification of the vehicle model was done in previous works hence only the PISC function had to be verified. In order to do that the cases that were going to be used during the clinics were tested to have results that could be used as a baseline for the simulator test results.

Due to the hardware limitations the clinics were performed without steering feedback. In order to have comparable results the verification was done using an arbitration that overrides the driver inputs while the PISC is engaged.

The driver model used is a simple model that determines the behaviour of the driver. In this verification, accelerating on a straight road was simulated (driver steering angle = 0^o, accelerator pedal fully pressed and brake pedal not pressed) with the driver becoming unconscious after the impact (driver steering angle = 0^o, accelerator pedal and brake pedal not pressed).

5.2 Test Cases

To evaluate the function two test cases were selected that would produce different post impact states so that the function efficiency could be tested. The test cases were tuned in order to obtain specified post impact states and are represented in figure 5.1. The post impact states should be somewhat difficult for a driver to control but not as harsh as to make a car tip over or go into a completely uncontrollable situation.

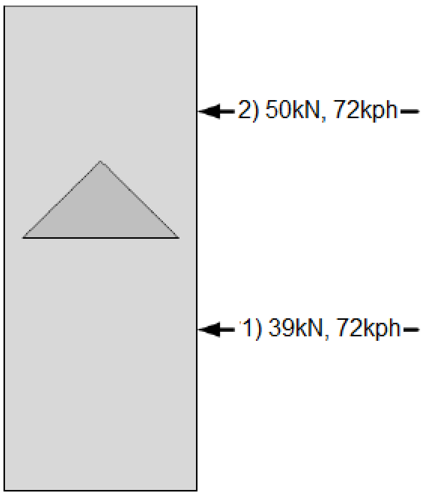

Figure 5.1: *Impact cases*

Table 5.1 defines the impact variables for the two test cases used in both the offline and the online simulations. The impact cases were tuned to obtain the post impact states presented in figure 5.2.

Table 5.1: Impact definition variables

	Impact case 1	Impact case 2
Impact Force [kN]	39	50
Impact angle [°]	90	90
Position x [m]	-0.2	0.3
Position y [m]	-0.6	-0.6
Position z [m]	0	0
Impact Speed [kph]	72	72

Table 5.2 defines the post-impact states obtained in the offline simulation that are used as reference in the online simulations to evaluate the simulator performance.

Table 5.2: Post-impact states

	Impact case 1	Impact case 2
Yaw Angle [°]	-3.263	5.346
Yaw Rate [°/s]	-34.19	52.95
Side Slip Angle [°]	12.51	7.31
Longitudinal Speed [kph]	70.98	72.66

5.3 Steering Feedback

To verify the steering feedback setup two separate tests were set up. One where the driver steering input is constant at zero, simulating that the driver grips the steering wheel firmly and holds it stationary, and one where the torque applied to the steering wheel by the driver is set to zero, simulating that the driver lets go of the steering wheel.

In the first case the generated driver steering angle input to the model was set to zero for the duration of the simulation.

In the second case a dynamic modelling of the steering system was introduced, described in equations (5.1) and (5.2)

$$\omega = \dot{\phi} \tag{5.1}$$

$$J\dot{\omega} = T_d - T_{fb} \tag{5.2}$$

where ϕ is the steering wheel angle, J the inertia of the steering column, T_d the torque applied to the steering wheel by the driver and T_{fb} the calculated feedback torque. T_d is kept at zero for the duration of the simulation.

5.4 Results

The two impact cases were simulated and the results plotted to use as a reference and to verify the performance of the PISC function.

In both cases the PIB (Post Impact Braking) function (cf. [KM12]) is used either immediately after impact or after the PISC function disengages.

All the plots are simulated from 0.2s before impact starts to 1s after impact ends. The impact itself lasts 0.2s and only after the end of the impact does the PISC function triggers.
For all the dynamic states plots the impact response is shown in green and scaled from 0 to 10.

5.4.1 Impact Case 1

Figures 5.2 to 5.6 represent the vehicle states for impact case 1 both with the PISC function on (in blue) and with the PISC function off (in red).

In figure 5.2 it can be seen that without the PISC function the longitudinal speed reduces faster than with the PISC function. This is due to the faster intervention of the PIB that brakes harder than the PISC function that tries to gain control of the car before braking. The end of impact occurs at 0.4 seconds.

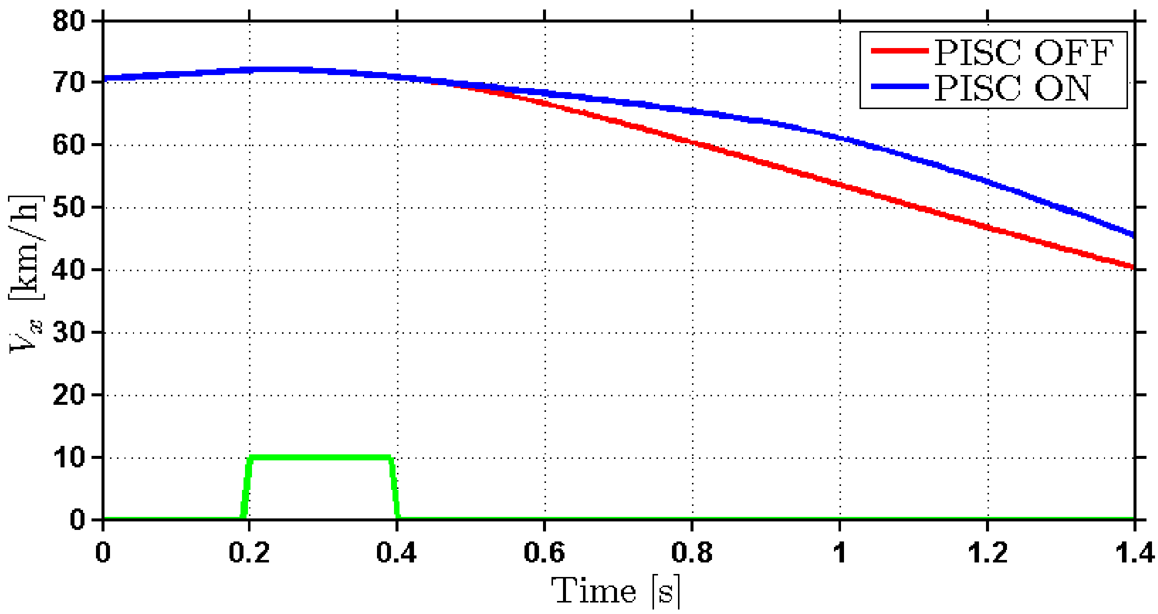

Figure 5.2: *Longitudinal speed for impact case 1*

In figure 5.3 it can be seen that without the PISC function the vehicle lateral speed is less than with the PISC function. This occurs for the same reasons presented for the longitudinal speed reduction, the PISC function does not break as hard as the PIB function.

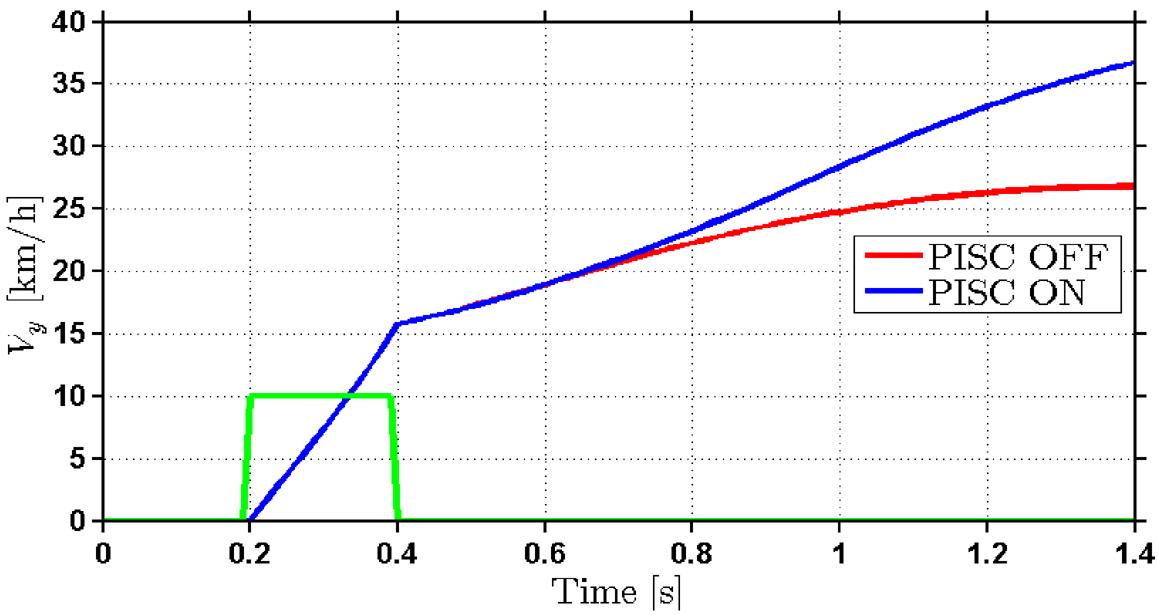

Figure 5.3: *Lateral speed for impact case 1*

In figure 5.4 it can be seen that the yaw angle is quite similar but that when the PISC is activated the yaw angle takes higher negative values. This is probably due to the steering intervention of the PISC function that tries to redirect the car to the lane it was in at the time of impact.

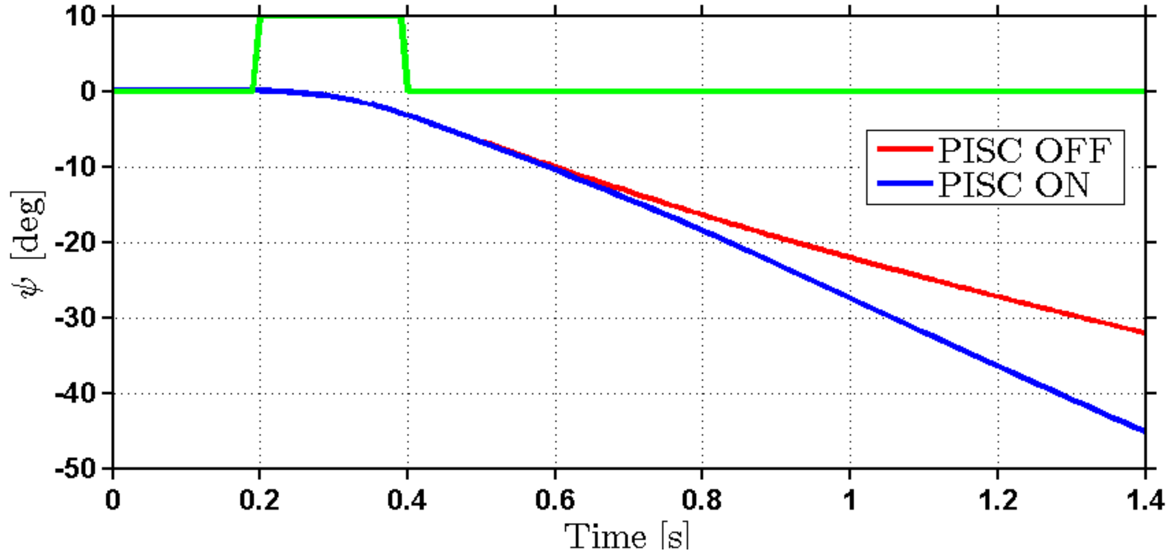

Figure 5.4: *Yaw angle for impact case 1*

In figure 5.5 it can be seen that immediately after the end of impact the case where the PISC is activated is lower but after the PISC is turned off it increases above the values for the case where the PISC is turned off. This is caused by the PISC steering and braking intervention that reduce the slip of the vehicle in the attempt of reducing the lateral deviation.

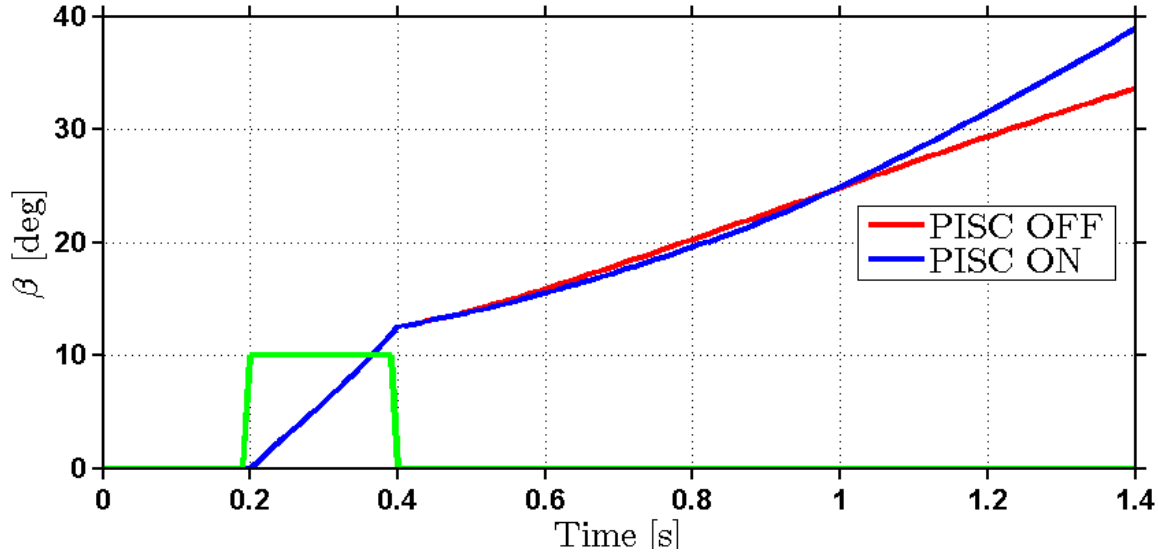

Figure 5.5: *Side slip angle for impact case 1*

In figure 5.6 it can be seen that the yaw rate when the PISC is on is bigger in absolute value than when the PISC is turned off. Since the impact is in the rear right of the car the yaw rate is already negative and the steering needed to minimise the lateral deviation will increase the value of the yaw rate.

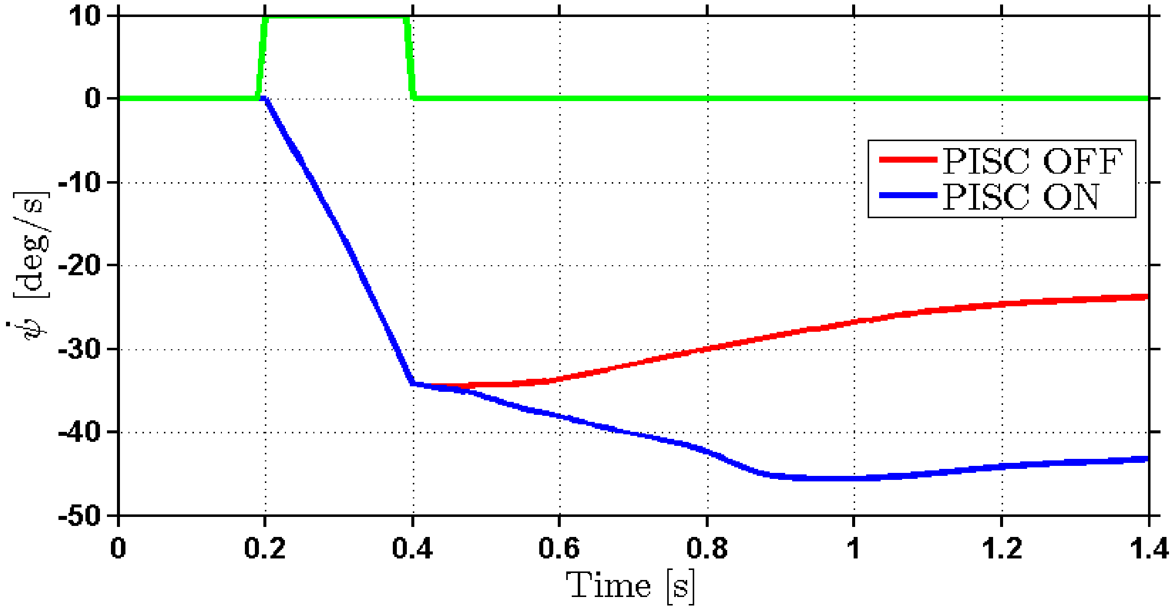

Figure 5.6: *Yaw rate for impact case 1*

In figure 5.7 it can be seen that the case where the PISC is activated has a maximum lateral deviation 0.5 meters smaller than the case where the PISC is turned off. With the PISC function turned on the vehicle deviated 1.08 metres while with the PISC off it deviated 1.64 metres.However when the PISC is on the vehicle travelled a longer longitudinal distance before stopping. The green line marks the instant where the PISC is disengaged.

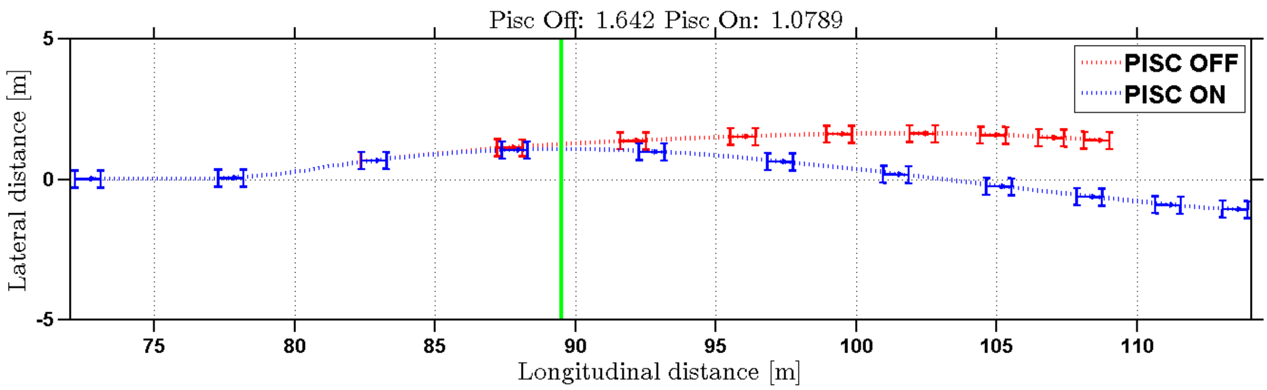

Figure 5.7: *Vehicle path for impact case 1*

5.4.2 Impact Case 2

Figures 5.8 to 5.12 represent the vehicle states for impact case 1 both with the PISC function on (in blue) and with the PISC function off (in red).

The end of impact occurs at 0.4 seconds, in the same instant the PISC figure turns on.

In figure 5.8 it can be seen that without the PISC function the longitudinal speed reduces faster than with the PISC function. This is due to the faster intervention of the PIB that brakes harder than the PISC function that tries to gain control of the car before braking.

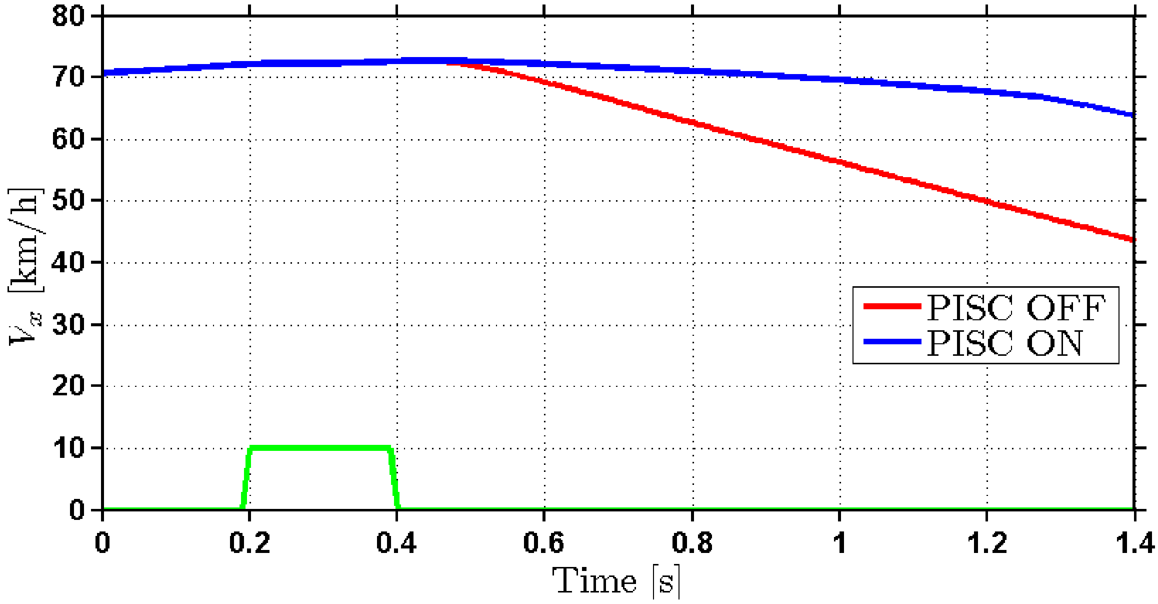

Figure 5.8: *Longitudinal speed for impact case 2*

In figure 5.9 it can be seen that without the PISC function the lateral speed is negative while with the function it is positive. This is due to the steering and the braking actuation that directs the car in the direction opposite to which it was going after the impact.

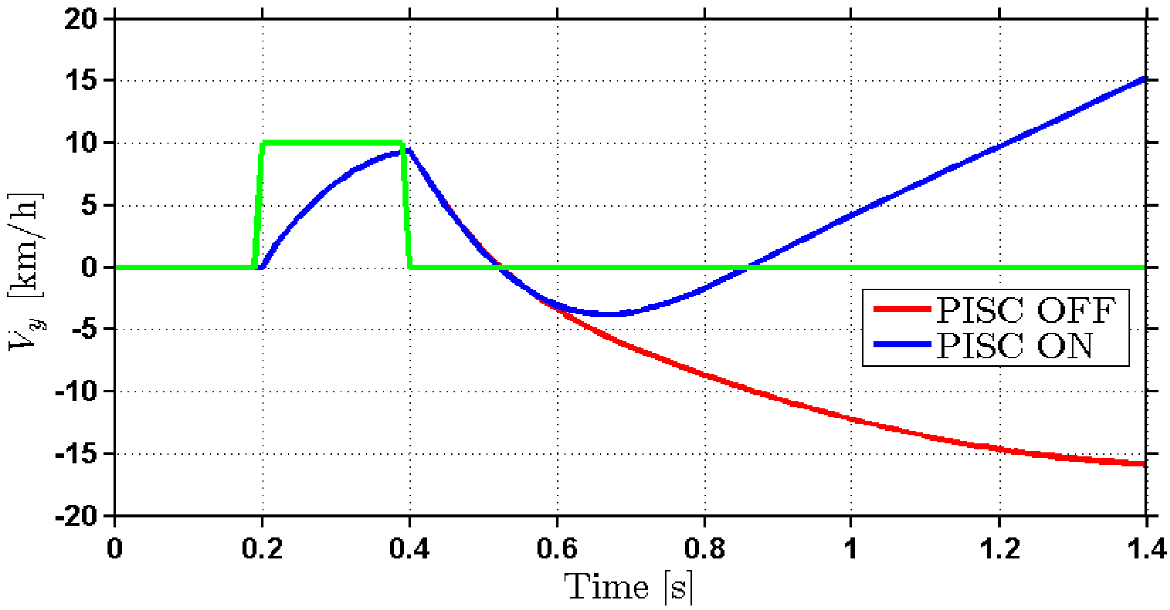

Figure 5.9: *Lateral speed for impact case 2*

In figure 5.10 it can be seen that the yaw angle decreases in the case where the PISC function is on and continues to increase in the case where it is off. This also due to the function intervention.

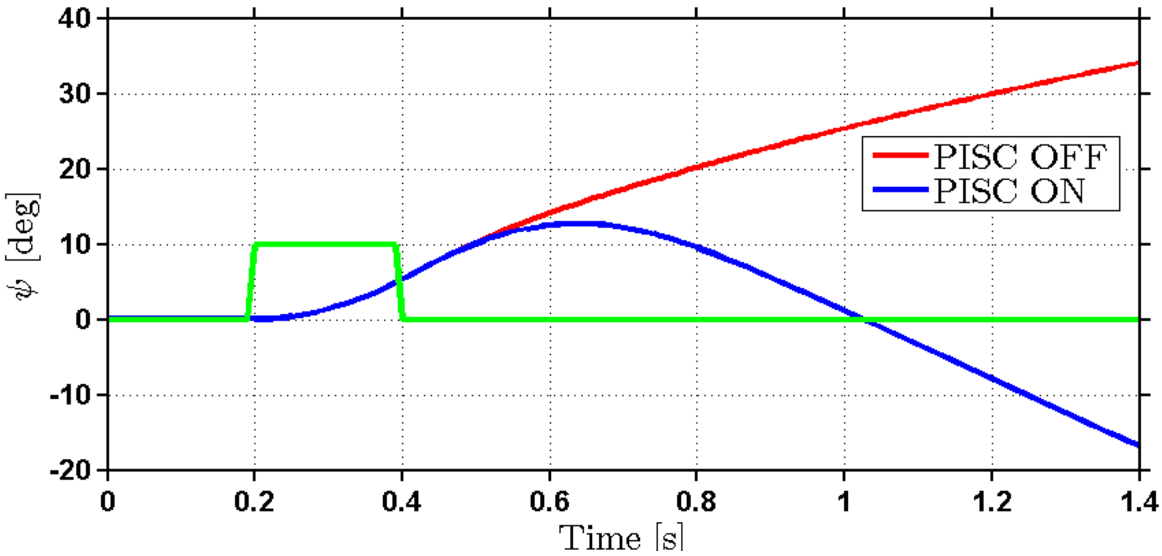

Figure 5.10: *Yaw angle for impact case 2*

In figure 5.5 it can be seen that the side slip angle increases when the PISC function is on and decreases when it is off. This is due to the PISC correcting the vehicle path in the direction opposing its movement.

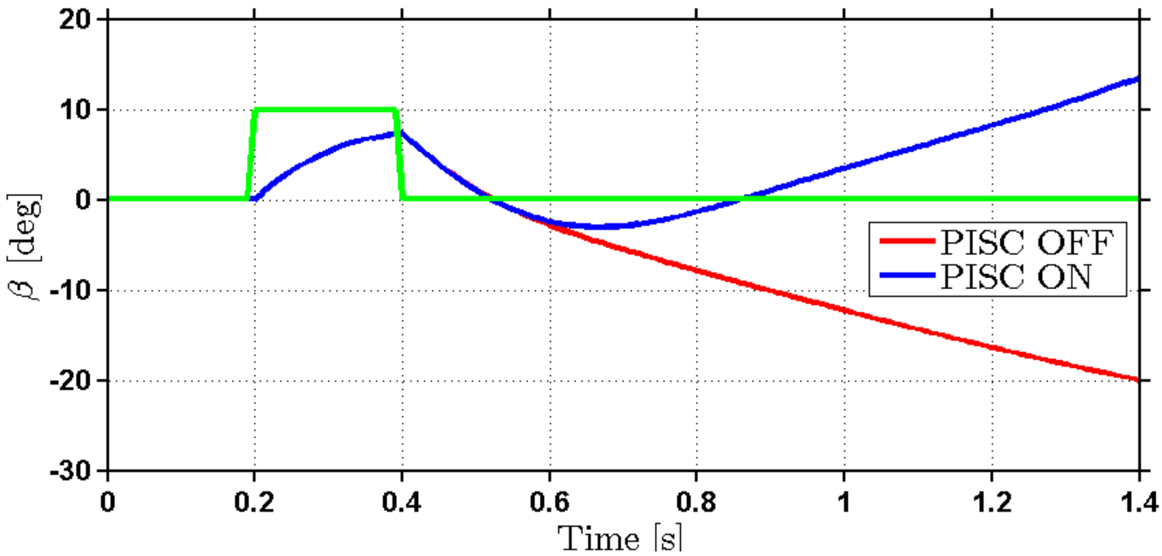

Figure 5.11: *Side slip angle for impact case 2*

In figure 5.12 it can be seen that the yaw rate when the PISC function is on it decreases to negative values while when the PISC function is off it only decreases slightly. This happens because of the steering intervention of the PISC function.

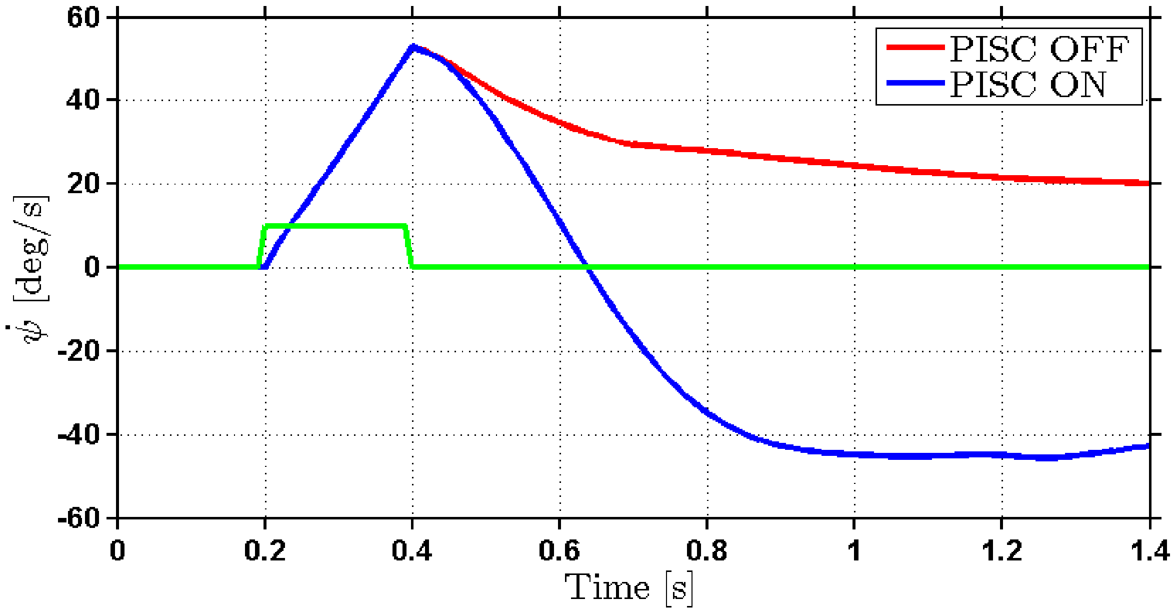

Figure 5.12: *Yaw rate for impact case 2*

In figure 5.13 it can be seen that the case where the PISC is activated as a maximum lateral deviation 2.38 metres smaller than the case where the PISC is turned off. With the PISC function turned on the vehicle deviated 2.51 meters while with the PISC off it deviated 7.09 meters. However when the PISC is on the vehicle travelled a longer longitudinal distance before stopping.The green line marks the instant where the PISC is disengaged.

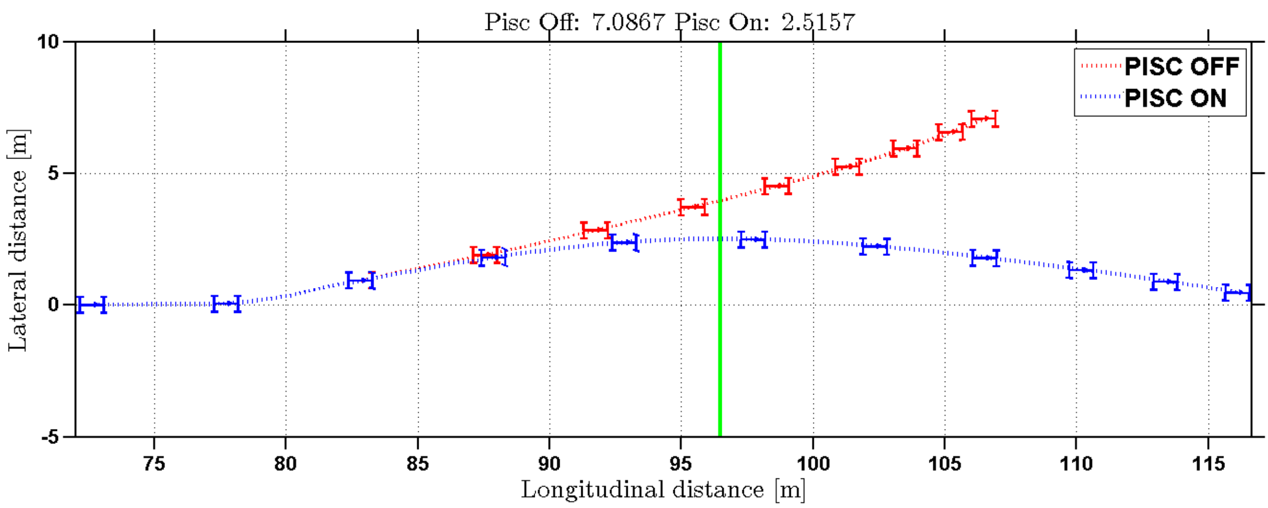

Figure 5.13: *Vehicle path for impact case 2*

5.4.3 Proof of concept for steering arbitration

For the proof of concept of the developed steering feedback model impact case 2 was used since it is a more violent impact and therefore causing a more difficult to control situation. It is also important to note that for these two extreme test cases the PISC function never disengages since it never reaches a Y_{max} due to the lack of actual steering.

Clinic setup

Figure 5.14 shows the PISC requested angle and the actual steering wheel angle for the steer by wire setup with the PISC function on. In this case the steering wheel angle is exactly the angle requested by the PISC function.

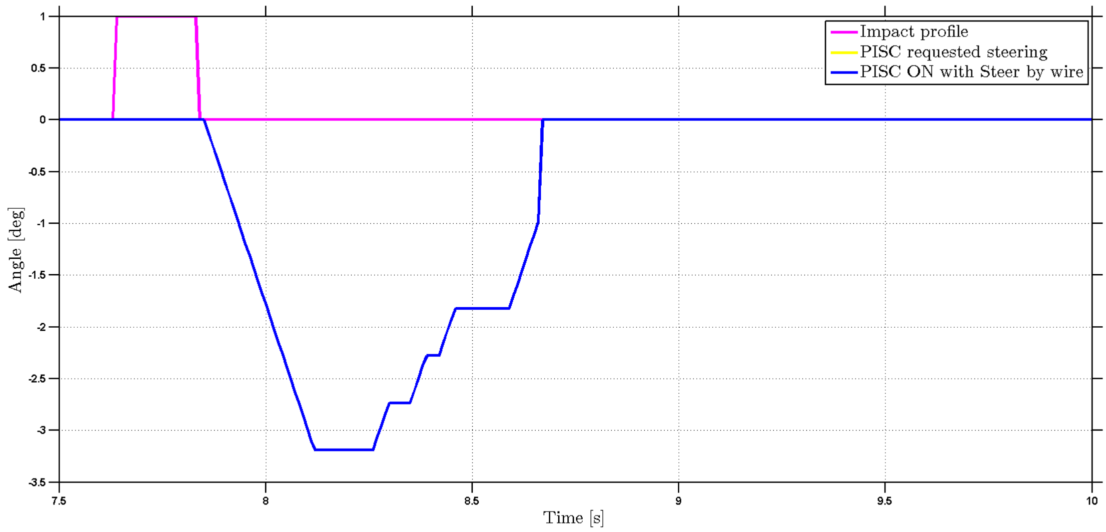

Figure 5.14: *Steering wheel angle response for PISC ON with Steer by wire (yellow curve covered by the blue curve)*

Figure 5.15 shows the feedback torque (self-aligning torque and PISC requested torque) for the steer by wire setup with the PISC function on. This case allows for a observation of the effect of the torque felt on the steering wheel. The dip in the torque feedback is caused by the abrupt return of the steering wheel to the 0° position. The torque then returns to the 4 Nm level due to the self-aligning torque.

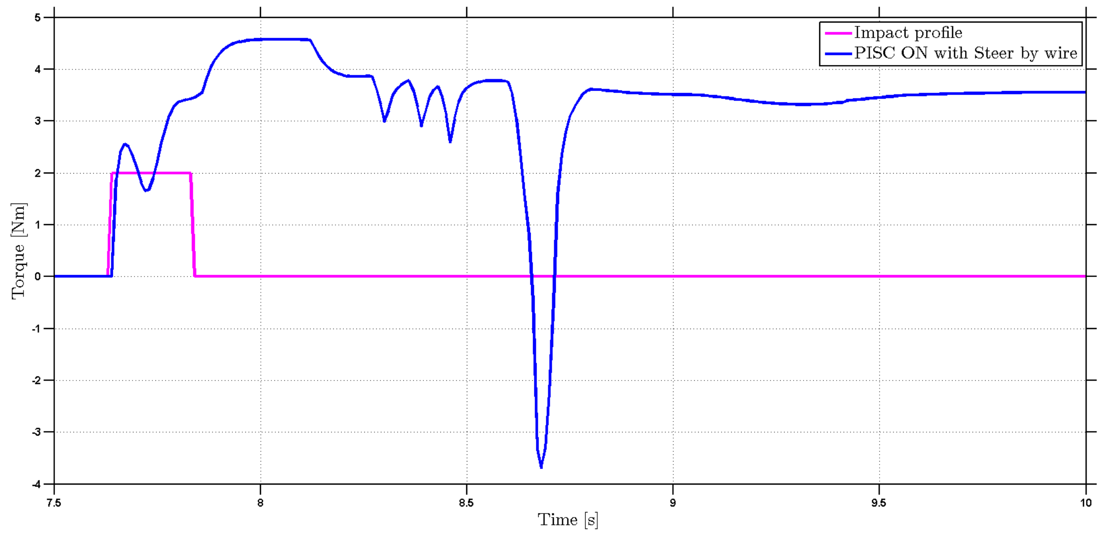

Figure 5.15: *Torque feedback response for PISC ON with Steer by wire*

Figure 5.16 shows an observation of the torque the driver would have to input to the model described by equations 5.1 and 5.2 to have the same behaviour as the steer-by-wire implementation. This torque is quite high, however it can be tuned to lower values by tuning the steering feedback gains.

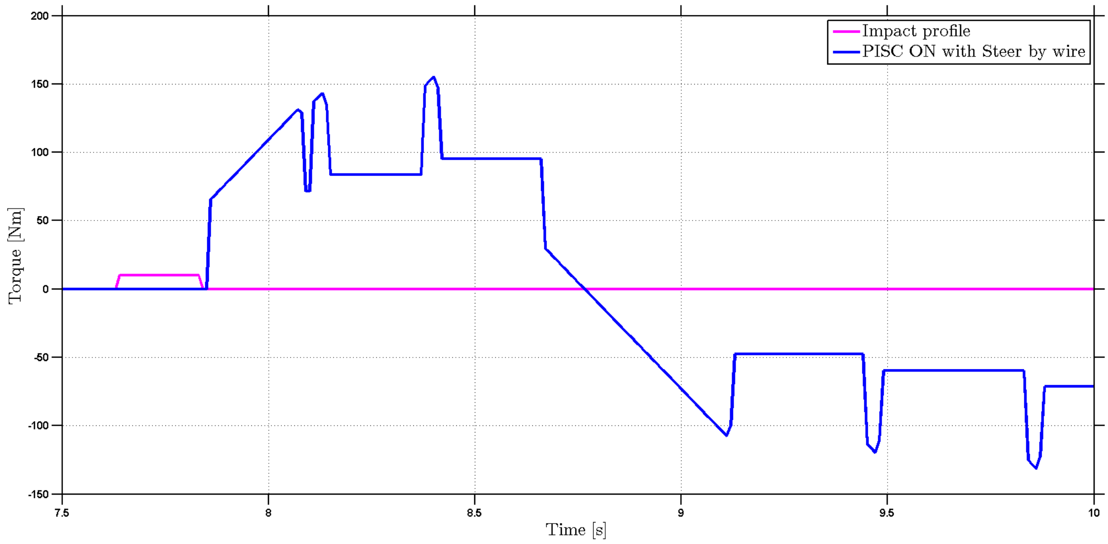

Figure 5.16: *Torque requested to the Driver for PISC ON with Steer by wire*

Driver holds steering wheel to zero angle

Figure 5.17 shows the steering wheel angle for the case with the PISC OFF and the steering wheel angle set at 0°.

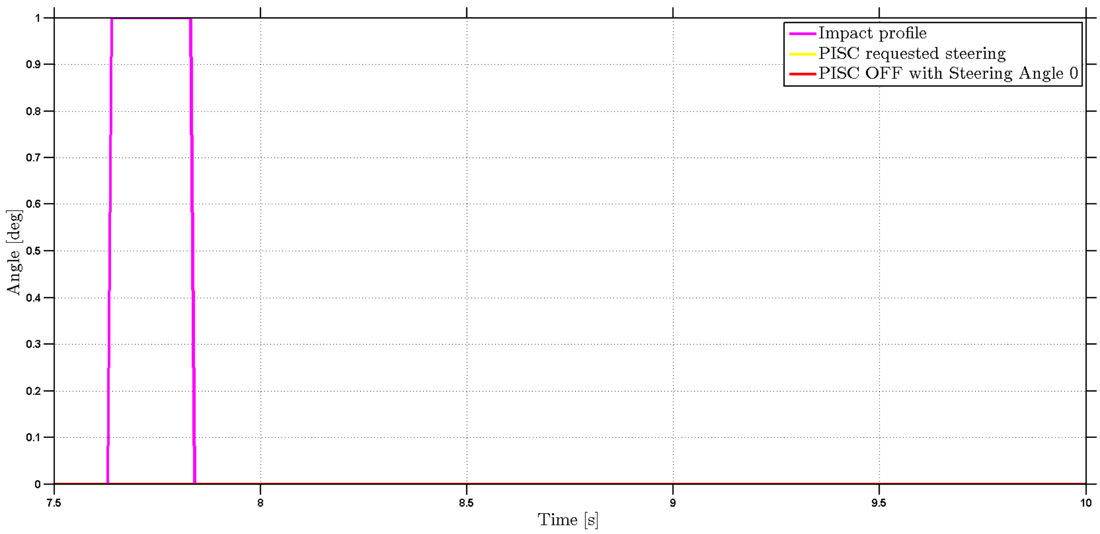

Figure 5.17: *Steering wheel angle response for PISC OFF with steering angle 0°*

Figure 5.18 shows the steering wheel torque for the case with the PISC OFF and the steering wheel angle set at 0°.

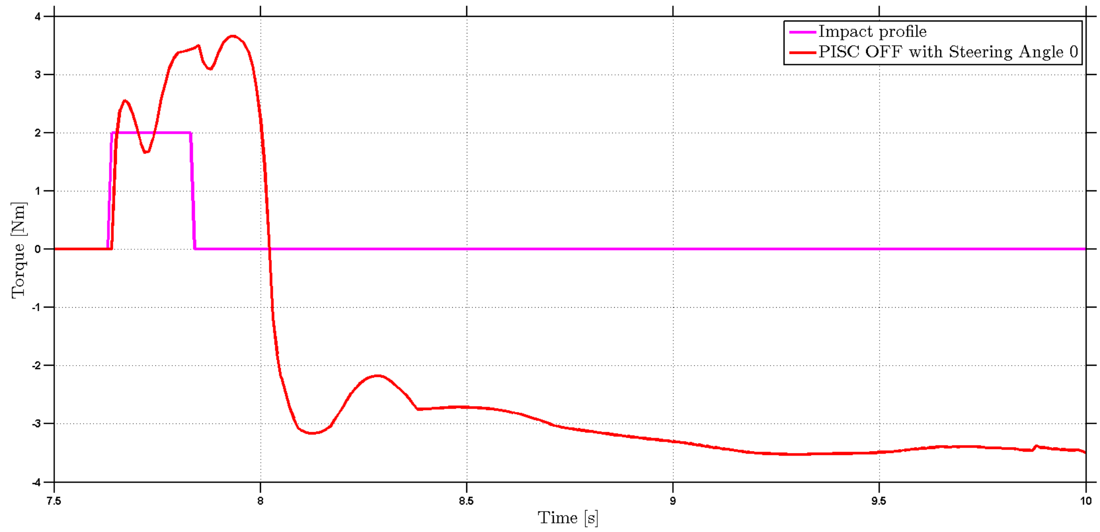

Figure 5.18: *Torque feedback response for PISC OFF with steering angle 0°*

Figure 5.19 shows the steering wheel angle for the case with the PISC ON with EPAS and the steering wheel angle set at 0°.

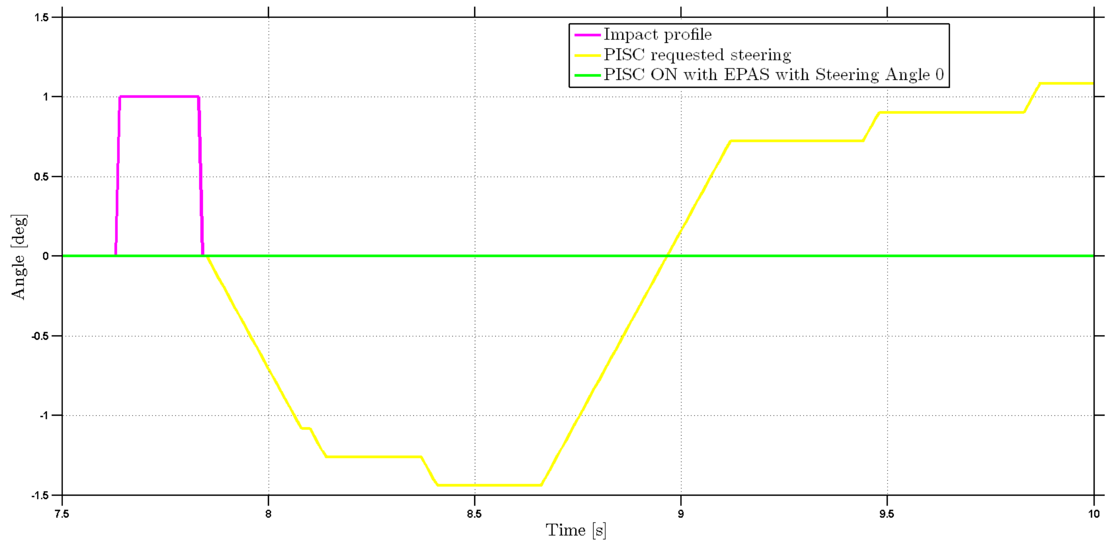

Figure 5.19: *Steering wheel angle response for PISC ON with EPAS with steering angle 0°*

Figure 5.20 shows the steering wheel torque for the case with the PISC ON with EPAS and the steering wheel angle set at 0°. It can be seen that the feedback torque tries to make the driver steer in the correct direction but that the moments involved are dangerously high, enough to potentially injure the driver.

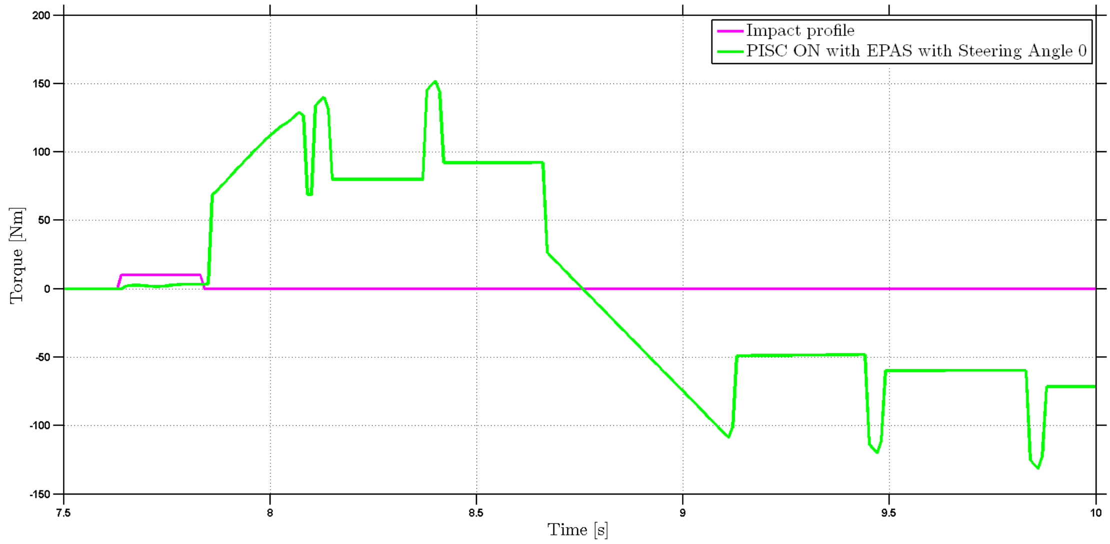

Figure 5.20: *Torque feedback response for PISC ON with EPAS with steering angle 0°*

Figure 5.21 represents the path for impact case 2 with and without PISC and for the case where the driver forces the steering angle to be 0. The path for this case is as expected since the driver will not allow the car to steer and it will not have the PIB function active at any instant reducing the distance travelled by the vehicle.

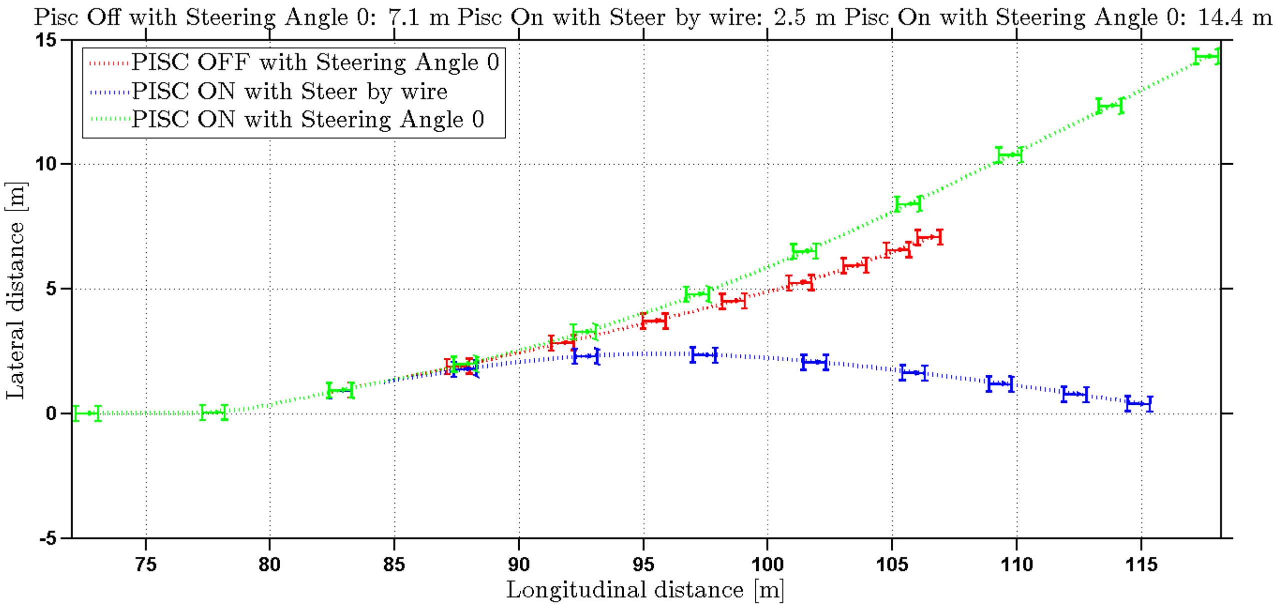

Figure 5.21: *Vehicle path for impact case 2 with Driver steering angle 0*

Driver releases the steering wheel to zero torque

Figure 5.22 shows the the steering wheel angle for the case with the PISC OFF and the driver torque set at 0 (driver releases the steering wheel). Since PISC is turned off only the self aligning torque is affecting the steering wheel angle. It can be seen that the angle diverges rapidly from acceptable values. This is probably due to instabilities in the driver model since the gains, as well as the simulation accuracy, were changed to find a stable response.

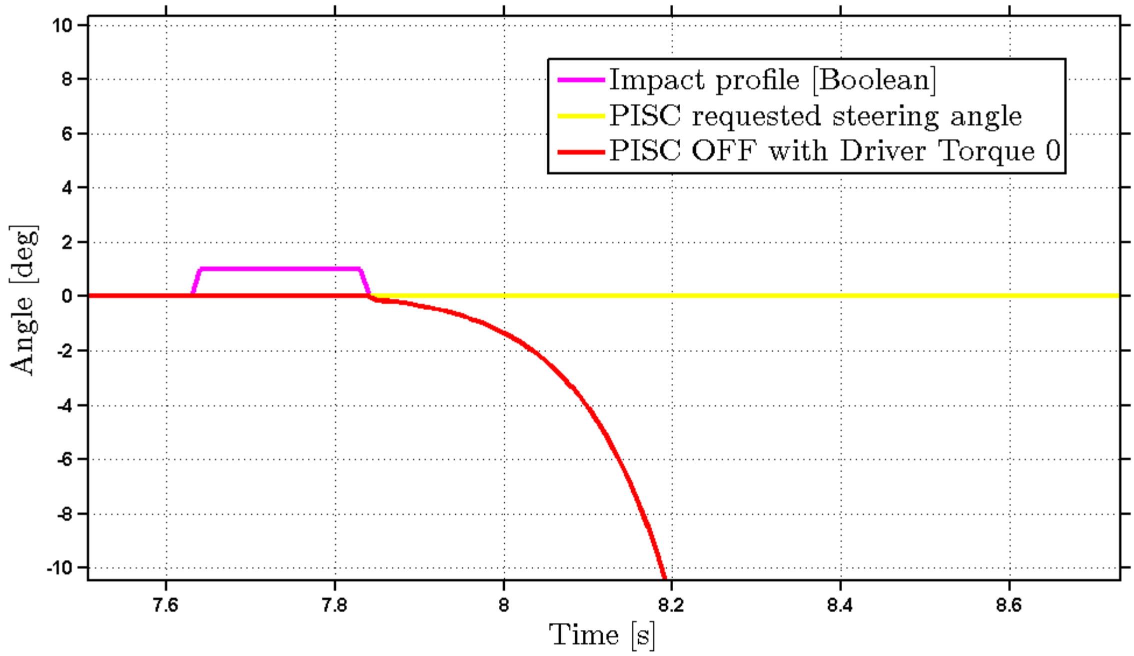

Figure 5.22: *Steering wheel angle response for PISC OFF with driver torque 0*

Figure 5.23 shows the the steering wheel torque for the case with the PISC OFF and the driver torque set at 0. It can be seen that the torque diverges rapidly to extremely high values. The reasons for this are the same as for the instabilities in the angle response. The steering wheel torque is only affected by the self-aligning torque since the driver let go of the wheel and the PISC is turned off.

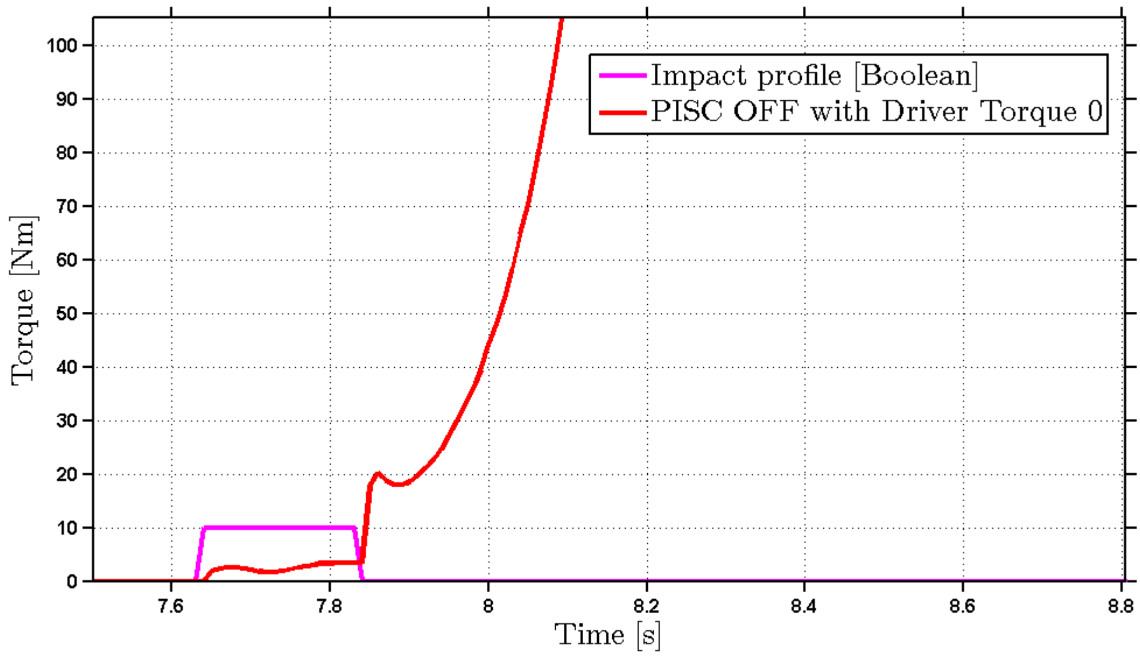

Figure 5.23: *Torque feedback response for PISC OFF with driver torque 0*

Figure 5.24 shows the the steering wheel angle for the case with the PISC ON with EPAS and the driver torque set at 0 (driver releases the steering wheel). It can be seen that the angle follows the requested steering quite acceptably. The requested steering angle is lower than the actual steering angle due to the gains used.

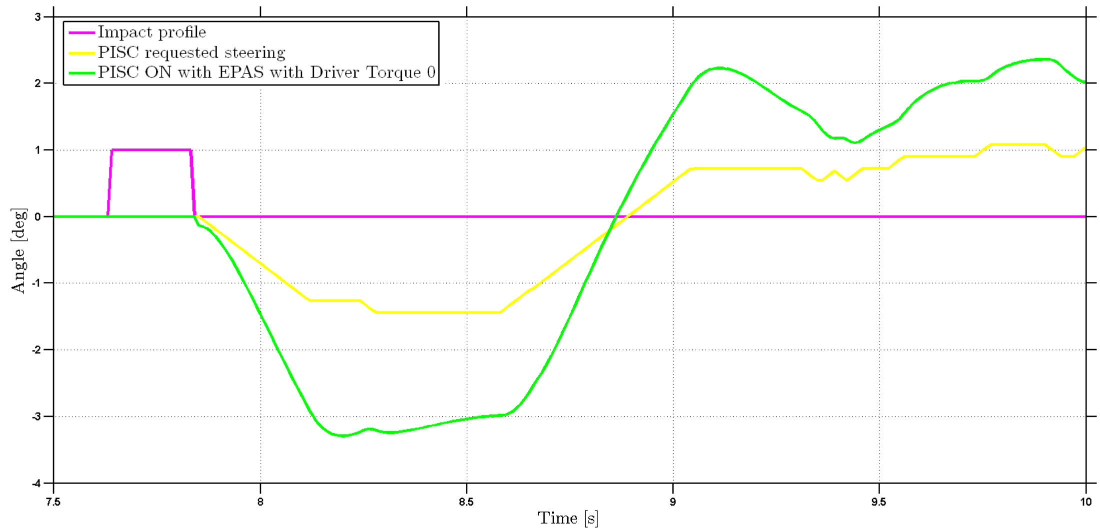

Figure 5.24: *Steering wheel angle response for PISC ON with EPAS with driver torque 0*

Figure 5.25 shows the the steering wheel torque for the case with the PISC ON with EPAS and the driver torque set at 0. It can be seen that the torque tries to control the steering wheel angle to ensure the correct steering.

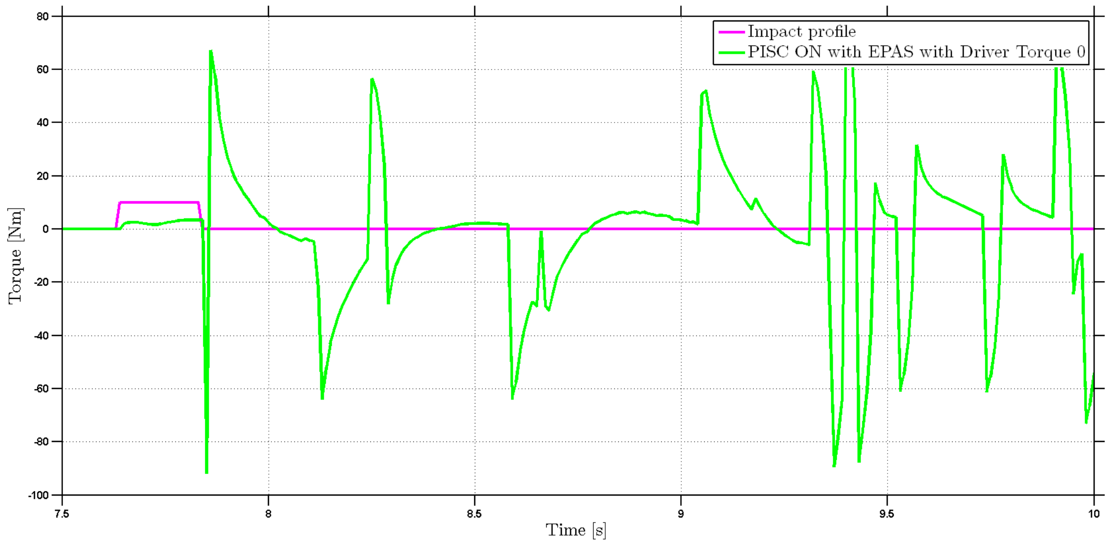

Figure 5.25: *Torque feedback response for PISC ON with EPAS with driver torque 0*

The instabilities seen in figures 5.22 to 5.25 is likely due to the absence of damping in the driver modelling. A method to avoid this instability can is found in [Swi+06].

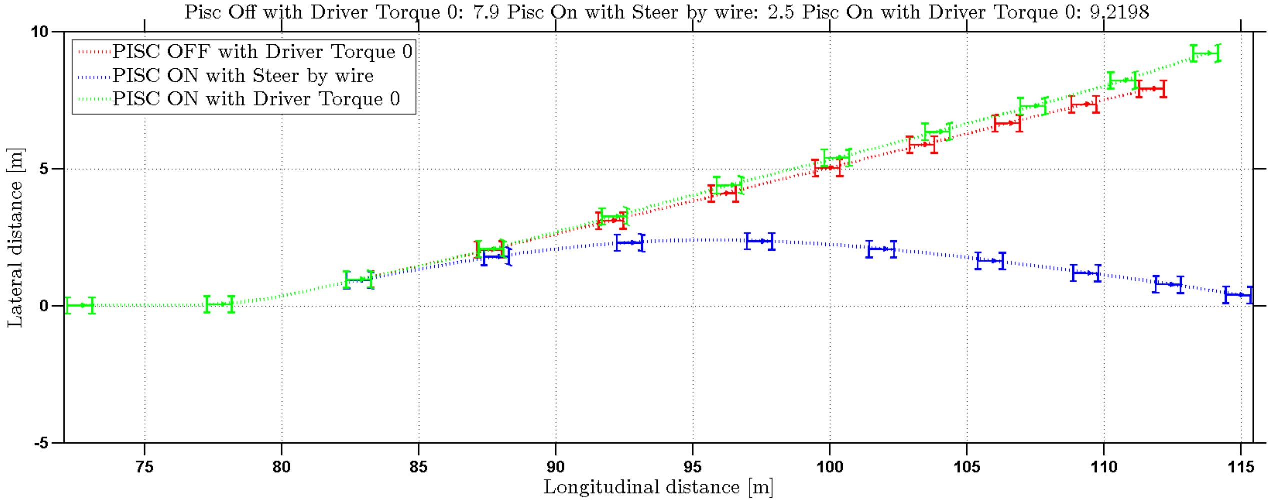

Figure 5.26: *Vehicle path for impact case 2 with Driver steering torque 0*

Figure 5.26 represents the path for impact case 2 with and without PISC and for the case where the driver torque is 0, meaning that the driver released the steering wheel. This case is does not behave quite as expected since the PISC function ends up overcompensating leading the vehicle to move even further away from the lane, this can be caused by inaccurate tuning of the PD controller. Since the gains in the controller produce higher steering angle values than for the optimal case (cf 5.24) the vehicle might react too fast and end up in the wrong direction. This case should be studied further and the gains tuned to optimality.

In figure 5.27 and 5.28 the brake forces from the time of impact to the moment the vehicle is fully stopped for the case where the PISC function is engaged both with the steer by wire configuration and the EPAS configuration with the driver torque at 0.

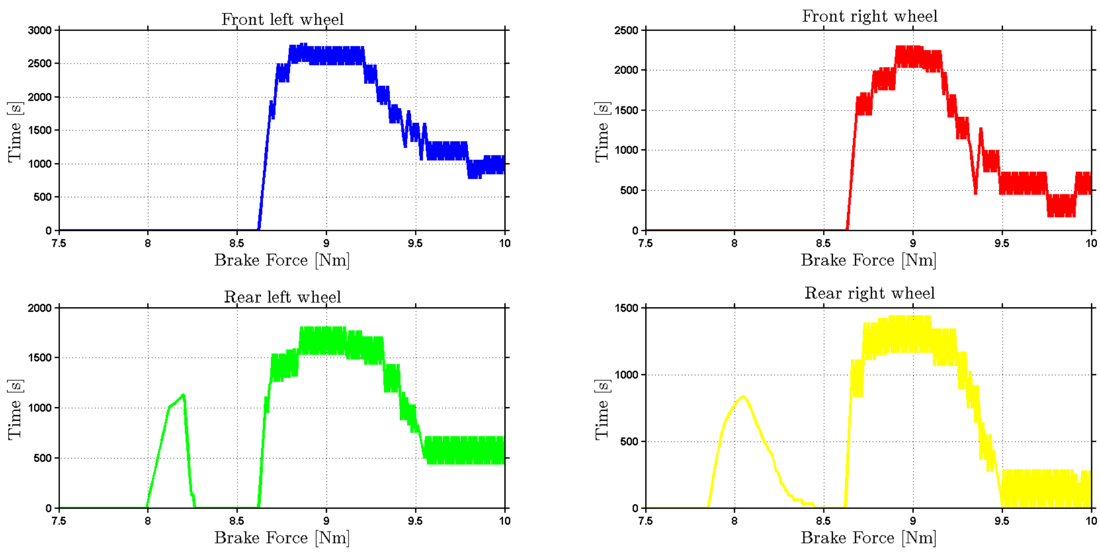

Figure 5.27: *Brake forces for each wheel with PISC ON with Steer by wire*

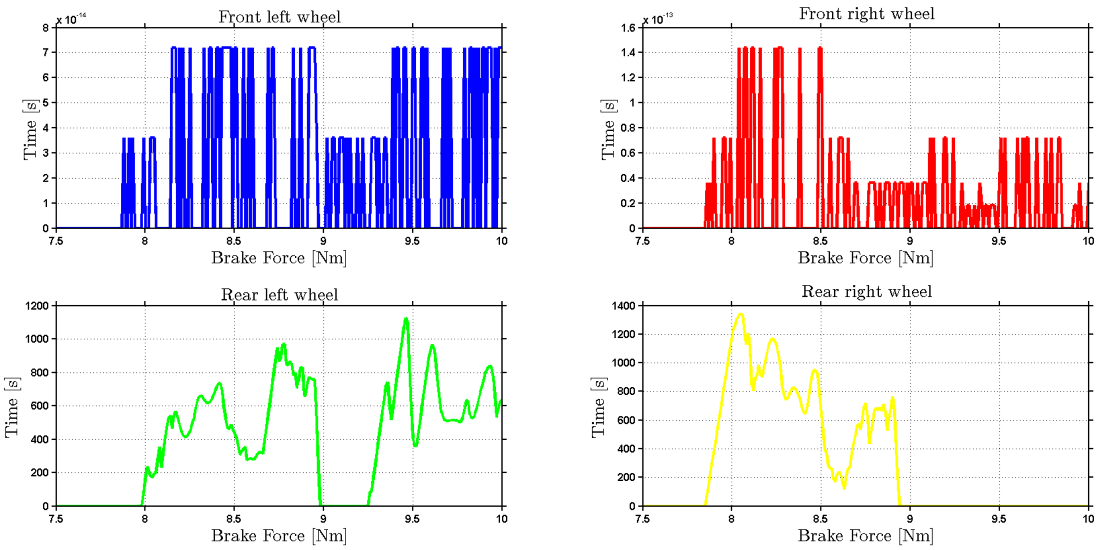

Figure 5.28: *Brake forces for each wheel with PISC ON with EPAS with Driver Torque 0*

It can be seen that the forces applied in the front wheels are quite different. This can be due to the calculated brake request being smaller due to the larger calculated steering request. This might be the reason why the vehicle deviates a lot more with the Driver Torque at 0 even with PISC function engaged.

6 Clinics

The simulator test were performed with a set of 32 volunteering test drivers divided in 4 test cases. All tests were performed at the Chalmers S2 simulator.

The driver simulator ensures the repeatability of the tests so that the results are scientifically valid and comparable for statistical purposes and an objective evaluation of the function.

However the simulator presents several issues that surfaced during the implementation of the model. The steering wheel feedback is nonexistent due to a problem in the DC motor that is supposed to provide it and the motion platform broke down possibly due to accumulation of dust in the pistons.

6.1 Method

In order to verify the function tests with real drivers were performed. Both to evaluate the drivers response to the function and to check the robustness of the algorithm while trying to compensate for varying driver inputs.

For these reasons and within the scope of the thesis, real drivers had to be subjected to mild impacts in order to have accurate and usable results that would prove the efficiency of the function in the real world.

In order to safeguard the drivers physical and mental health the tests were be conducted in a safe and controlled environment, a driving simulator, where safety thresholds were implemented to avoid to abrupt impacts and risks to the well being of the test drivers.

Each test was run either with PISC turned on or off and with one out of the two impact cases. The purpose of dividing the cases is to both be able to compare the effect on the post impact states by PISC and to evaluate two different kinds of impacts.

The test cases used are defined in table 5.1.

At each test the driver was first instructed to drive freely to get accustomed to the vehicle and later to drive according to ongoing instructions from the supervisor. Then the driver was instructed to go from a stand still to a designated speed at which point an impact would be induced automatically as the vehicle reaches the target speed designated in the control panel. In order to have genuine reactions from the drivers any notion that an impact was to be part of the study was deliberately kept from them.

In order to have a more subjective analysis of the setup the test subjects were asked to answer a questionnaire regarding the experiment and their feeling towards what they experienced.

6.2 Test Subjects

In order to keep the results statistically valid the group of participants in the test was chosen to be as homogeneous as possible. According to the research note *Comparison of Crash Fatalities by Sex and Age Group* [Cha08] the group most prone to be involved in car crashes are people between the ages of 21 and 25, thus the candidates were chose to match that criterion as closely as possible. An additional criterion was that the candidates were to have some driving experience, preferably having a drivers license for at least two years.

6.3 Results

This section presents and describes the results obtained during the clinics, for both impact cases both with and without PISC.

6.3.1 Driver reaction time

The reaction time were calculated as the time difference between the moment the impact starts and the moment where either the steering wheel input or the brake pedal input crossed a threshold that could be considered a reaction. The thresholds used were:

- Braking - 20% of maximum brake pedal engagement
- Steering - Turning the steering wheel 10°

Not all the drivers reacted hence the results are for the values of only 27 of the 32 test subjects. The drivers that did not react were removed from the calculations.

Table 6.1: Braking and steering reaction times for impact cases 1 & 2

	Min [s]	Max [s]	Mean [s]
Braking case 1	1.182	16.312	3.6854
Steering case 1	0.05	2.233	0.4856
Braking case 2	1.101	10.166	3.6009
Steering case 2	0.052	1.392	0.3884

In some cases the driver seems to react inhumanly fast which is most likely due to the driver initiating a braking/steering action moments before the impact which then triggers the reaction time thresholds.

Figures 6.1 to 6.4 displays the spreads for the reaction times of the initial braking (red) and steering (blue) reactions.

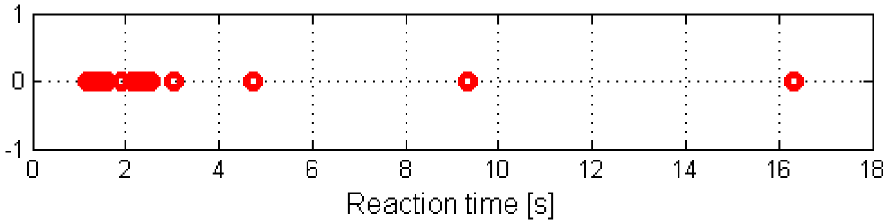

Figure 6.1: *Impact case 1 brake reaction time spread*

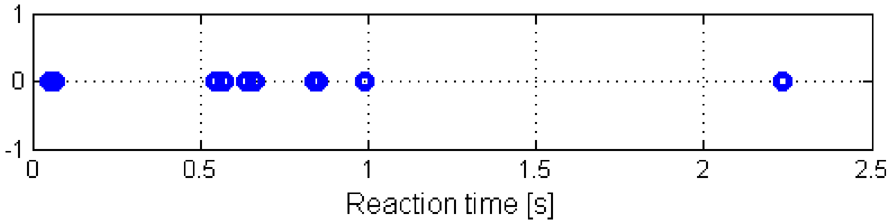

Figure 6.2: *Impact case 1 steer reaction time spread*

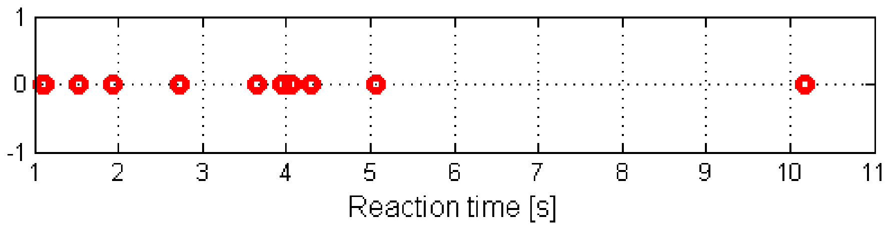

Figure 6.3: *Impact case 2 brake reaction time spread*

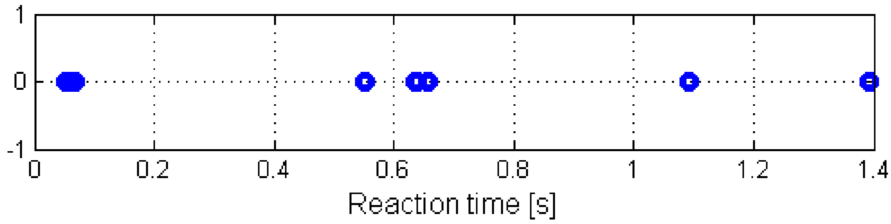

Figure 6.4: *Impact case 2 steer reaction time spread*

Overall the drivers tried to steer before braking most likely to either try to regain control or due to starting a steering manoeuvre right before impact.

Figure 6.5 shows an example of how the driver inputs vary during a clinic.

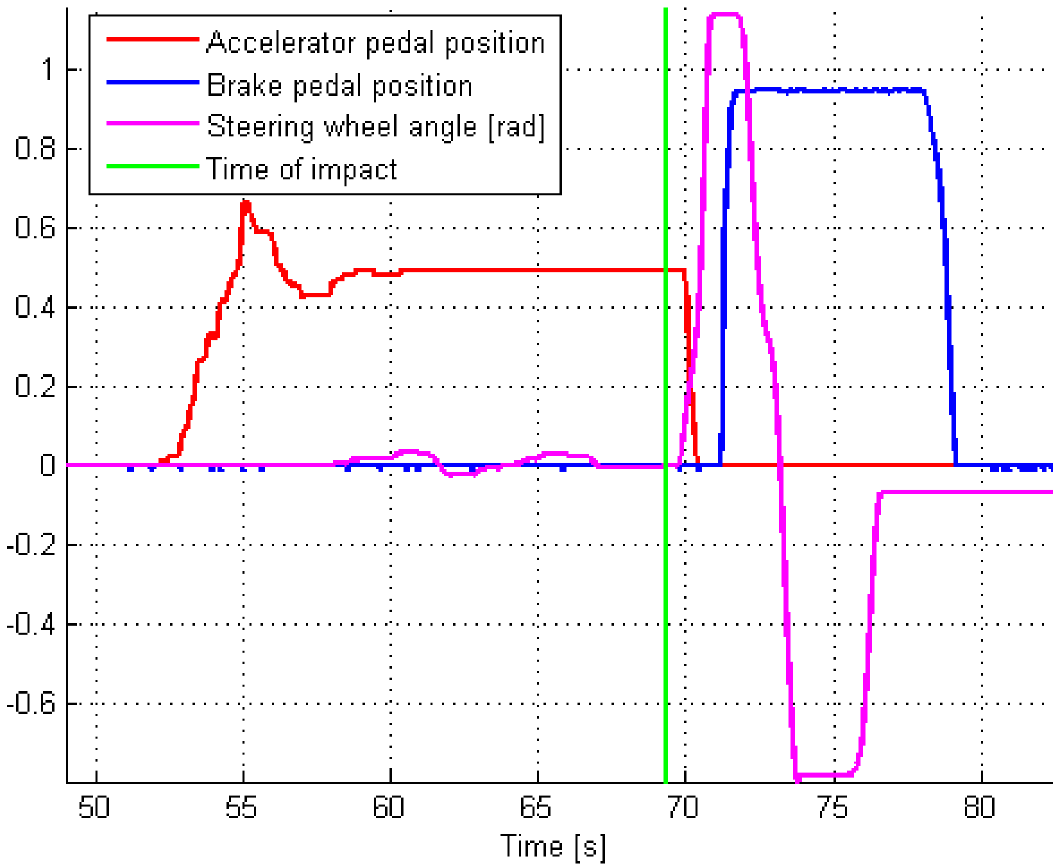

Figure 6.5: *Driver pedal positions during an example clinic*

In the above example a few instants after the impact the driver releases the accelerator pedal and starts steering. After a few instants more the driver starts to rapidly apply pressure to the braking pedal instead and steering the other way trying to counter the vehicle movement.

6.3.2 Longitudinal and Lateral deviations

Figure 6.6 shows the positions at Y_{max} for the different cases relative to each other and the x value for which they occur.

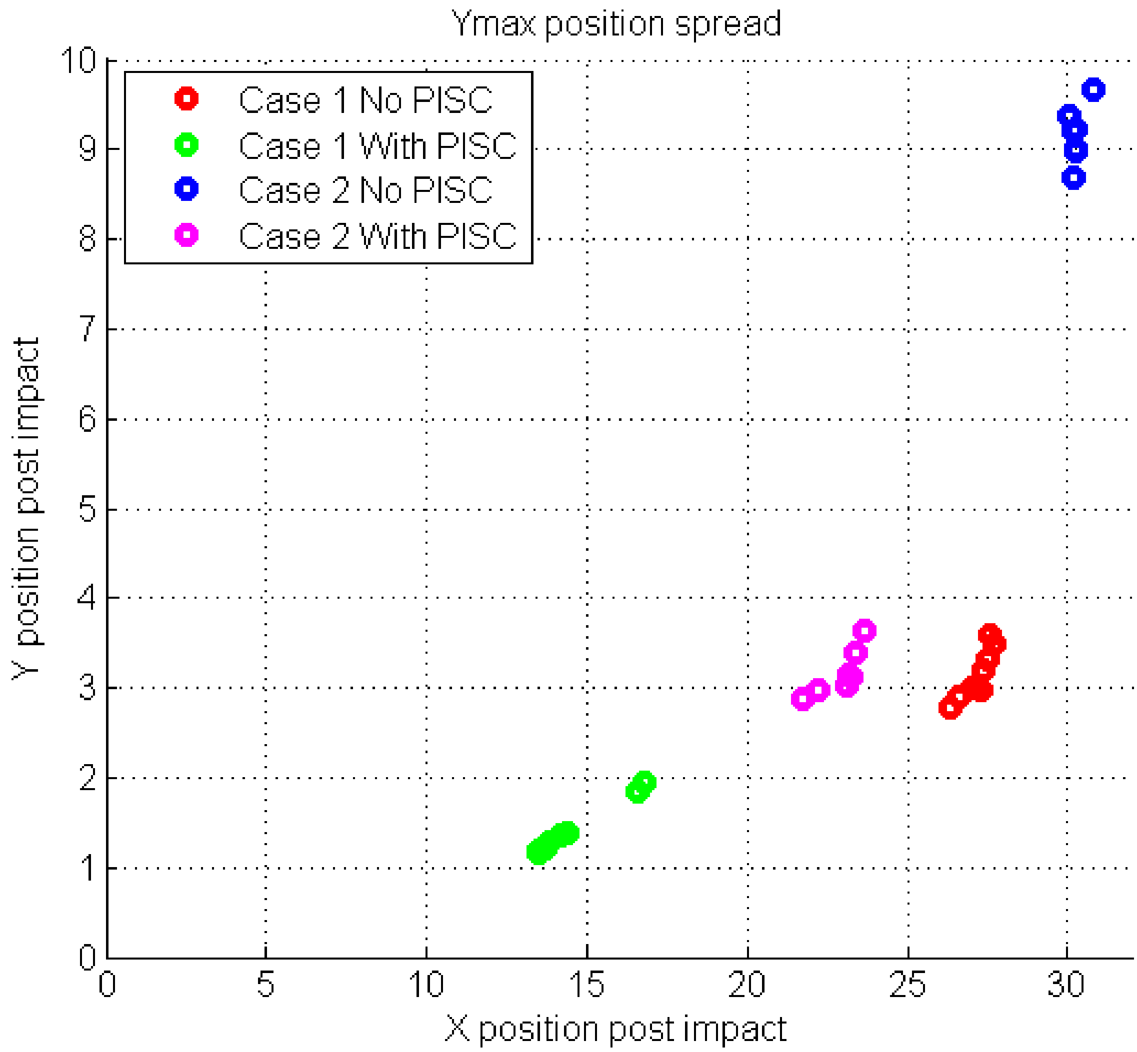

Figure 6.6: Y_{max} *position spread*

In figure 6.6 the origin represents the car's position at the time of impact. The general trend is that with PISC Y_{max} is reduced and occurs at shorter distances travelled from the impact.

However the longitudinal speed when Y_{max} is reached when the PISC is On implies that a much longer distance will be needed to reach standstill as can be seen in figure 6.7.

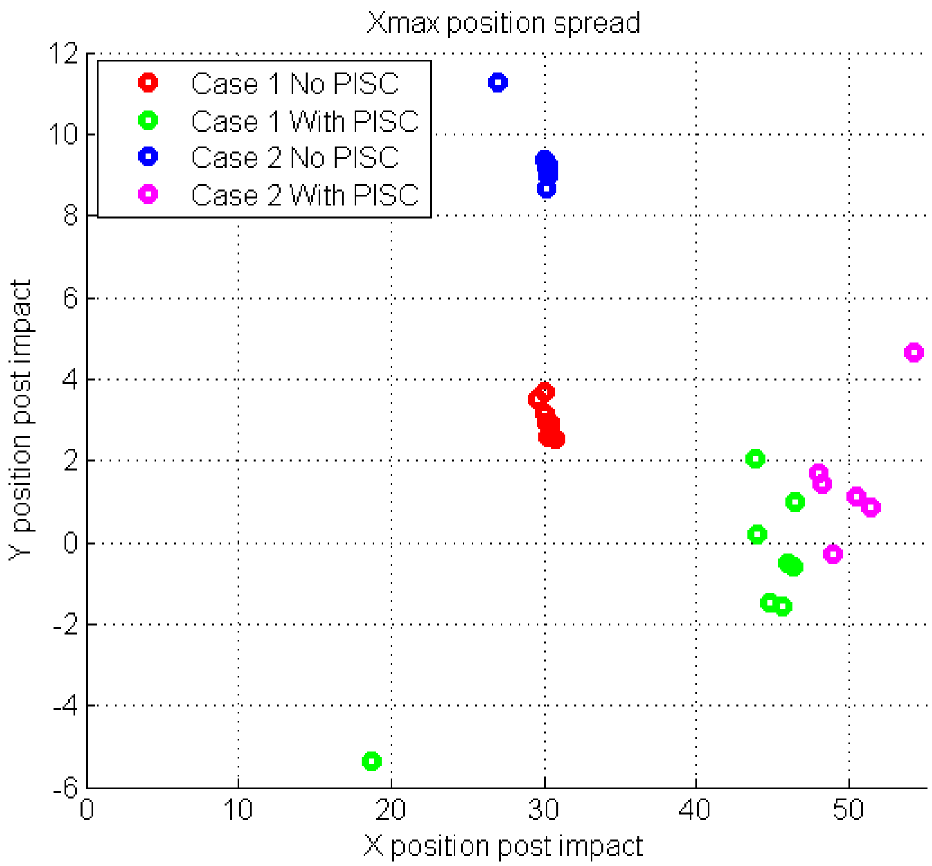

Figure 6.7: *Xmax position spread*

As can be seen in figure 6.7 the cases where the PISC is On reach standstill further down the road, which was predictable due to the design of the function and its subsequent intervention. However the PISC function still ensures that the driver can take control of the car after the PISC has been disengaged

6.3.3 Other Post Impact States

The post impact states obtained from the clinics can indicate if the vehicle model behave as expected when compared to the offline model and can also ensure that the PISC function was well tuned for the case in question and therefore if the results are valid.

Tables 6.2 and 6.3 present the post impact states for impact case 1 and 2 respectively.

Table 6.2: Online post impact states case 1

	Min	Max	Mean
Longitudinal Speed [km/h]	69.49	72.48	71.07
Lateral Speed [km/h]	11.78	13.62	12.73
Yaw Angle [°]	-1.72	-3.26	-2.40
Side Slip Angle [°]	12.26	12.79	12.56
Yaw Rate [°/s]	-27.10	-35.77	-31.41

Table 6.3: Online post impact states case 2

	Min	Max	Mean
Longitudinal Velocity [km/h]	68.32	72.18	70.60
Lateral Velocity [km/h]	16.35	18.79	17.12
Yaw Angle [^{o}]	5.40	12.23	6.55
Side Slip Angle [^{o}]	3.14	7.47	7.09
Yaw Rate [^{o}/s]	53.91	104.52	59.71

The results present in tables 6.2 and 6.3 are quite consistent with each other except for an outlier for impact case 2. The outlier is test 23 and the result without the outlier are present in the table 6.4, this outlier should influence the results of the Y_{max} calculations.

Table 6.4: Online post impact states case 2

	Min	Max	Mean
Longitudinal Velocity [km/h]	69.15	72.18	70.75
Lateral Velocity [km/h]	16.36	18.00	17.00
Yaw Angle [^{o}]	5.40	6.97	6.17
Side Slip Angle [^{o}]	7.22	7.47	7.35
Yaw Rate [^{o}/s]	53.91	60.04	56.72

6.3.4 PISC OFF

An interesting set of results are the dynamic states when the car leaves the lane. For the purposes of this thesis the lane was 3.75 m wide. Considering a car driving in the centre of the lane it was defined that for a car to leave the lane to a dangerous extent the car had to deviate 2 m from the centre of the lane. The results for the cases where PISC was off are presented in tables 6.5 to 6.10.

Table 6.5: Longitudinal velocity when leaving the lane with PISC OFF

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	53.94	58.21	55.73
Impact Case 2	60.35	61.53	60.66

Table 6.6: Lateral velocity when leaving the lane with PISC OFF

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	5.34	7.48	6.36
Impact Case 2	14.06	17.62	14.82

Table 6.7: Absolute velocity when leaving the lane with PISC OFF

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	54.21	58.69	56.09
Impact Case 2	61.97	64.00	62.45

Table 6.8: Yaw angle when leaving the lane with PISC OFF

	Min [^{o}]	Max [^{o}]	Mean [^{o}]
Impact Case 1	-12.92	-15.94	-14.56
Impact Case 2	22.45	34.03	24.03

Table 6.9: Side slip angle when leaving the lane with PISC OFF

	Min [°]	Max [°]	Mean [°]
Impact Case 1	20.03	21.98	21.06
Impact Case 2	-18.05	-8.88	-10.31

Table 6.10: Yaw rate when leaving the lane with PISC OFF

	Min [°/s]	Max [°/s]	Mean [°/s]
Impact Case 1	-15.40	-19.50	-17.17
Impact Case 2	38.77	83.36	46.25

Table 6.11 shows the Y_{max} results from the clinics that were run without the PISC function, utilising only PIB for post impact intervention.

Table 6.11: Y_{max} for PISC off

	Min [m]	Max [m]	Mean [m]
Impact case 1	2.79	3.58	3.16
Impact case 2	8.69	11.98	9.52

Judging from table 6.11 the second impact case was more difficult for the driver to handle.

Figure 6.8 shows the spread of Y_{max} measurements.

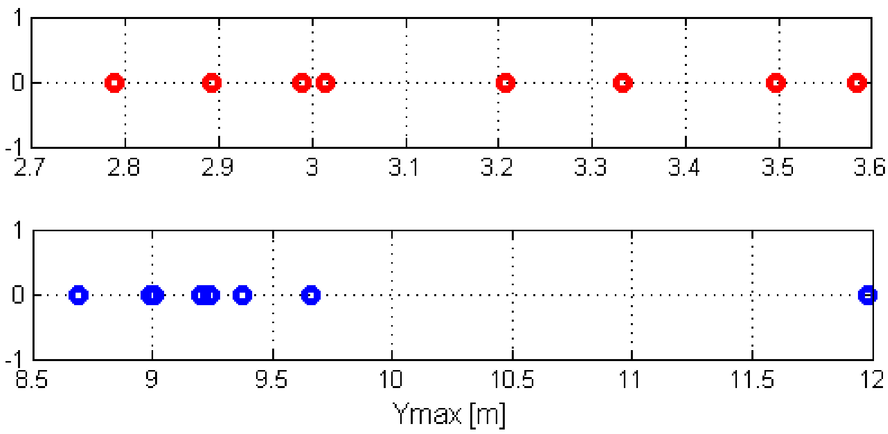

Figure 6.8: *Lateral deviation measurement spread for impact case 1 (red) and 2 (blue) without PISC*

Despite a slight outlier for impact case 2 the measurement spread seems reasonable. This outlier is caused by the difference noted in the post impact states. However, although having larger yaw rate and yaw angle the side slip was lower and since Y_{max} is not out of the scope of the other values and the test was performed without PISC the result will still be considered.

The following tables present the dynamic states at the instant where Y_{max} is reached for both case 1 and case 2 without the intervention of the PISC function.

Table 6.12: Longitudinal velocity at Y_{max} with PISC OFF

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	18.85	28.39	23.04
Impact Case 2	-0.01	20.65	2.58

Table 6.13: Lateral velocity at Y_{max} with PISC OFF

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	-0.45	-0.28	-0.33
Impact Case 2	-0.55	0.02	-0.06

Table 6.14: Yaw angle at Y_{max} with PISC OFF

	Min [^{o}]	Max [^{o}]	Mean [^{o}]
Impact Case 1	-29.33	-38.98	-34.69
Impact Case 2	131.32	174.06	141.79

Table 6.15: Side slip angle at Y_{max} with PISC OFF

	Min [^{o}]	Max [^{o}]	Mean [^{o}]
Impact Case 1	28.74	38.12	33.85
Impact Case 2	8.57	-175.58	-60.30

Table 6.16: Yaw rate at Y_{max} with PISC OFF

	Min [^{o}/s]	Max [^{o}/s]	Mean [^{o}/s]
Impact Case 1	-10.09	-18.60	-14.50
Impact Case 2	-0.17	26.86	3.32

The dynamic states at Y_{max} are important because they indicate the position of the vehicle and can be used to evaluate the evolution of the car states when compared with the post-impact states.

Table 6.17 shows the maximum yaw angle values during the clinics for the cases without PISC.

Table 6.17: Maximum yaw angles with PISC OFF

	Min [^{o}]	Max [^{o}]	Mean [^{o}]
Impact case 1	34.2	58.5	47.4
Impact case 2	131.3	221.2	150.0

Figure 6.9 shows the spread of the maximum yaw angles.

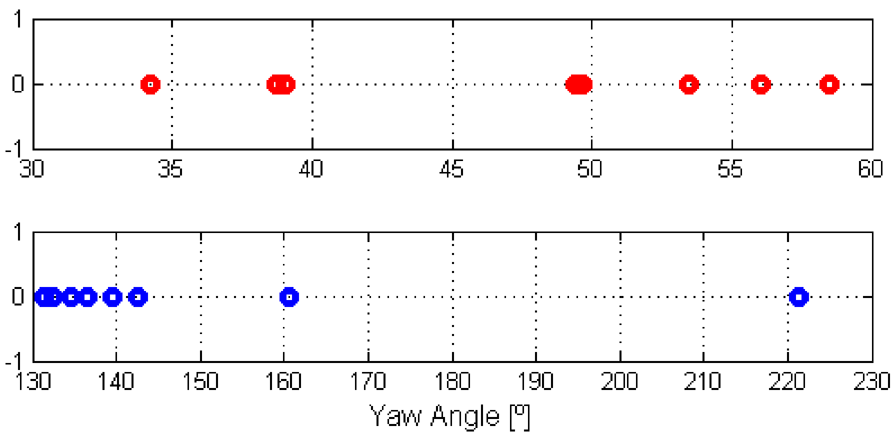

Figure 6.9: *Maximum yaw angle spread for impact case 1 (red) and 2 (blue) without PISC*

6.3.5 PISC ON

The dynamic states when leaving the lane for when the PISC is on are presented in tables 6.5 to 6.10. The same conditions as for when the PISC is off apply. When the vehicle does not leave the lane the values don't apply and are represented as NA (Not Applicable)

Table 6.18: Longitudinal velocity when leaving the lane with PISC ON

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	NA	NA	NA
Impact Case 2	70.99	73.16	72.32

Table 6.19: Lateral velocity when leaving the lane with PISC ON

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	NA	NA	NA
Impact Case 2	11.60	13.86	12.62

Table 6.20: Absolute velocity when leaving the lane with PISC ON

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	NA	NA	NA
Impact Case 2	72.33	74.24	73.42

Table 6.21: Yaw angle when leaving the lane with PISC ON

	Min [°]	Max [°]	Mean [°]
Impact Case 1	NA	NA	NA
Impact Case 2	11.37	14.28	12.53

Table 6.22: Side slip angle when leaving the lane with PISC ON

	Min [°]	Max [°]	Mean [°]
Impact Case 1	NA	NA	NA
Impact Case 2	-2.19	-3.22	-2.63

Table 6.23: Yaw rate when leaving the lane with PISC ON

	Min [°/s]	Max [°/s]	Mean [°/s]
Impact Case 1	NA	NA	NA
Impact Case 2	-30.66	-11.38	-23.98

It is important to observe that for the impact case 1 there are no values for the dynamic states when leaving the lane because it never leaves the lane it is on.

Table 6.24 shows the Y_{max} results from the clinics where both PISC and PIB were utilized in the post impact intervention.

Table 6.24: Y_{max} for PISC on

	Min [m]	Max [m]	Mean [m]
Impact case 1	1.18	1.94	1.43
Impact case 2	2.89	25.97	6.02

In table 6.24 the maximum value of Y_{max} for the second impact case deviates largely from the mean, this can be verfied by looking at figure 6.10 of lateral displacement measurement spreads.

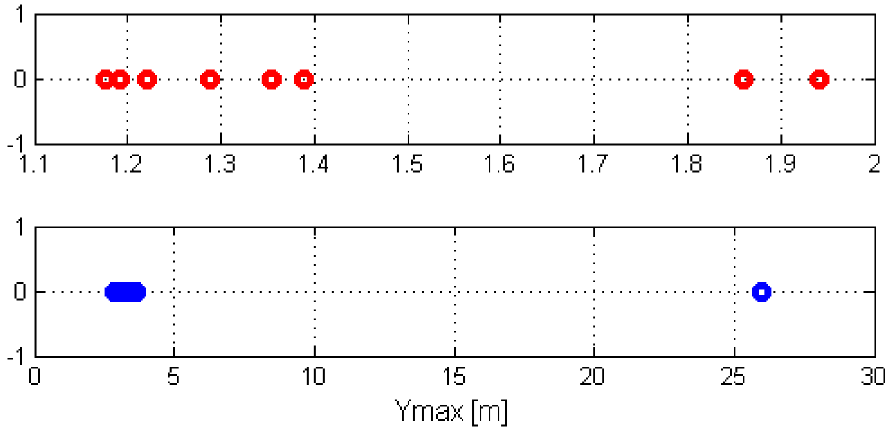

Figure 6.10: *Lateral deviation measurement spread for impact case 1 (red) and 2 (blue) with PISC*

As can be seen in figure 6.10 impact case 2 has a huge outlier, where the largest value is over 7 times as big as the second largest value. Experience from simulation procedures dictates the outlier can be disregarded as an anomaly which is dealt with in further detail in chapter Results.

Disregarding the outlier for impact case 2 makes the new values according to table 6.25.

Table 6.25: Y_{max} for impact case 2 with PISC

	Min [m]	Max [m]	Mean [m]
Old	2.89	25.97	6.02
New	2.89	3.63	3.17

The new values for impact case 2 are grouped much more tightly, with can also be seen in figure 6.11.

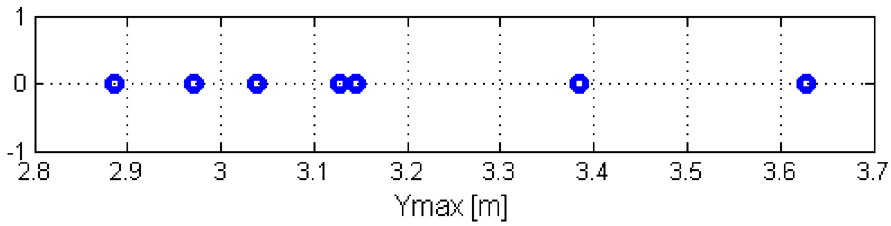

Figure 6.11: *Lateral deviation measurement spread for modified impact case 2 with PISC*

Comparing the spread for impact case 2 in figure 6.24 to figure 6.11 the latter seems more reasonable.

The following tables present the dynamic states at the instant where Y_{max} is reached for both case 1 and case 2 with the intervention of the PISC function. The outlier case was removed from this table and will no longer be considered while performing analysis of results

Table 6.26: Longitudinal velocity at Y_{max} with PISC ON

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	67.35	72.37	70.62
Impact Case 2	69.16	70.82	70.04

Table 6.27: Lateral velocity at Y_{max} with PISC ON

	Min [km/h]	Max [km/h]	Mean [km/h]
Impact Case 1	-0.51	-2.18	-1.07
Impact Case 2	-0.39	-1.64	-0.82

Table 6.28: Yaw angle at Y_{max} with PISC ON

	Min [°]	Max [°]	Mean [°]
Impact Case 1	-20.91	-28.92	-23.48
Impact Case 2	-11.47	-14.36	-13.18

Table 6.29: Side slip angle at Y_{max} with PISC ON

	Min [°]	Max [°]	Mean [°]
Impact Case 1	20.48	27.06	22.59
Impact Case 2	11.14	13.39	12.51

Table 6.30: Yaw rate at Y_{max} with PISC ON

	Min [°/s]	Max [°/s]	Mean [°/s]
Impact Case 1	-37.90	-45.48	-41.01
Impact Case 2	-27.57	-44.47	-37.58

The dynamic states at Y_{max} are important because they indicate the position of the vehicle and can be used to evaluate the evolution of the car states when compared with the post impact states. This can be used to evaluate the performance of the PISC function when comparing the states at Y_{max} for the cases where the PISC is on and where the PISC is off.

Table 6.31 shows the maximum yaw angle values during the clinics for the cases with PISC.

Table 6.31: Maximum yaw angles with PISC ON

	Min [°]	Max [°]	Mean [°]
Impact case 1	105.5	241.0	148.1
Impact case 2	17.7	171.6	94.3

Figure 6.12 shows the spread of the maximum yaw angles.

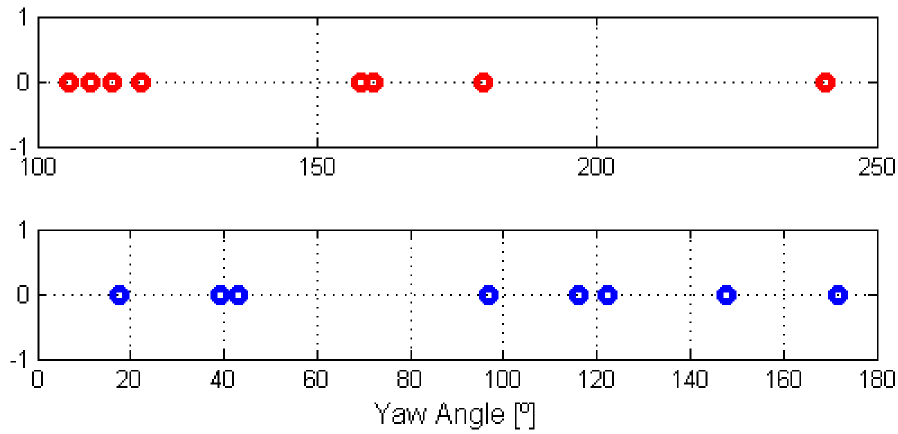

Figure 6.12: *Maximum yaw angle spread for impact case 1 (red) and 2 (blue) with PISC*

6.3.6 Questionnaire

The questionnaire answered by the test subjects (cf. Appendix B) gives a bit more insight into the functioning of the simulator as a reliable tool to emulate the driving feeling and also in to the way the drivers perceive the function to be tested.

The results are as follows.

Table 6.32: Answer to question 1 and 3 of the questionnaire

	Min [0-10]	Max [0-10]	Mean [0-10]
Stressful situation	0	7	2.19
Realistic simulator	1	8	4.75

As can be seen in table 6.32 most of the drivers said that the simulation was not stressful and realistic enough. This was probably due to the lack of motion in the simulator.

Regarding the impact only 62,5% of the drivers noticed that there was an impact. The others considered the impact a bug in the system or did not understand what happened.

62,5 % of the drivers said that they would have reacted differently in real life. 50 % said they were not satisfied with the type of reaction after impact and 40,63 % were not satisfied with the reaction time. 12,5 % said that this experience might help them in real life.

The control function was present in 50 % of the impact cases, however only 1 out of 16 noticed the presence of a control function and said that the function helped him because: "It reduced the speed and tried to keep the car safe on the road".

Some complaints were made about the simulator, such as the lack of steering feedback that made it hard to keep the car on the road and the lack of peripheral vision which made the sense of speed unrealistic. These are constraints that were taken under consideration while designing the clinics and that were deemed to have an influence which would not skew the results since it would be constant over all the tests.

7 Results

In this chapter the results from the clinics and the offline simulation will be analysed, in order, by:

- Comparing the offline results with the online (clinics) results.
- Comparing the clinics results with and without PISC to determine the benefits of the function.

7.1 Offline vs. Online results

Since the impact cases used were the same (cf. table 5.1) the post impact states should be the same. Since it is the same vehicle model. Some slight variations could exist due to the driver intervention right before or during the impact.

Tables 7.1 and 7.2 combines the results for the offline and online post-impact states for cases 1 and 2 respectively. The tables were created using the results for the offline model and the mean value of each of the states for each case in the clinic.

To evaluate the consistency between the online and the offline models the variation between them was calculated. The formula used is presented in equation 7.1.

$$variation = \frac{onlinemodel - offlinemodel}{offlinemodel} \times 100 \tag{7.1}$$

Table 7.1: Post impact states comparison for impact case 1

	Offline model	Online model	Variation
Longitudinal speed [km/h]	70.98	71.07	0.12%
Yaw angle [°]	-3.26	-2.40	-26.38%
Side slip angle [°]	12.51	12.56	0.40%
Yaw rate [°/s]	-34.19	-31.41	-8.13%

Table 7.2: Post impact states comparison for impact case 2

	Offline model	Online model	Variation
Longitudinal speed [km/h]	72.66	70.60	-2.84%
Yaw angle [°]	5.35	6.55	22.43%
Side slip angle [°]	7.31	7.09	-3.01%
Yaw rate [°/s]	52.95	59.71	12.77%

According to the tables above the values are quite consistent with the results obtained for the offline model. This is expected since the vehicle model is the same. The slight differences that exist might be related to the way the driver steers, accelerates and brakes during the tests.

The variation between values in the offline and the online model is always under 26.38 % and the higher variant cases are ones where the absolute value is quite small.

Overall the post impact states obtained are good enough to consider that the results for the clinics are valid and that the tuning of the PISC function is well designed.

The performance of the PISC function between the offline and the online model can also be compared. The variation of Y_{max} is calculated using equation 7.1.

Tables 7.3 and 7.4 present the values for each of the models, with and without PISC, for case 1 and 2 respectively.

Table 7.3: Y_{max} [m] for impact case 1

	PISC OFF	PISC ON	With PISC
Offline model	1.64	1.08	Better
Online model	3.16	1.43	Better

Table 7.4: Y_{max} [m] for impact case 2

	PISC OFF	PISC ON	With PISC
Offline model	7.09	2.51	Better
Online model	9.52	3.17	Better

It can be seen that although the values for the offline model are numerically smaller the impact of the PISC function in the online model is more beneficial. For case 1 the PISC function is 21 % more beneficial in the online model while in case 2 it is 18 % more beneficial.

Irregardless of the model the PISC function is deemed to have a positive impact in the lateral deviation and both the results for the offline and the online model are consistent.

Since these results are valid, the analysis of the performance of the PISC function can be executed. The results of that analysis is presented in section PISC on vs. PISC off for simulator tests.

7.2 PISC on vs. PISC off for simulator tests

In order to evaluate the efficiency of the PISC function Y_{max} and dynamic state values when leaving the lane are compared between having PISC present or not.

Tables 7.5 and 7.6 displays the comparisons when the vehicle leaves the lane for impact case 1 and 2 respectively. The mean values for each case are used for comparison. When the vehicle does not leave the lane the values don't apply and are represented as NA (Not Applicable)

Table 7.5: Clinic performance when leaving the lane comparison for impact case 1

	PISC off	PISC on	With PISC
Longitudinal velocity [km/h]	55.73	NA	Better
Lateral velocity [km/h]	6.36	NA	Better
Absolute velocity [km/h]	56.09	NA	Better
Yaw angle [^{o}]	-14.56	NA	Better
Side slip angle [^{o}]	21.06	NA	Better
Yaw rate [^{o}/s]	-17.17	NA	Better

Table 7.6: Clinic performance when leaving the lane comparison for impact case 2

	PISC off	PISC on	With PISC
Longitudinal velocity [km/h]	60.66	72.32	Worse
Lateral velocity [km/h]	14.82	12.62	Better
Absolute velocity [km/h]	62.45	73.42	Worse
Yaw angle [^{o}]	24.03	12.53	Better
Side slip angle [^{o}]	-10.31	-2.63	Better
Yaw rate [^{o}/s]	46.25	-23.98	Better

In table 7.5 the vehicle never left the lane when PISC was on, meaning the results are listed as Not a Number (NaN). Overall the case where the PISC is on performs better, reducing practically every state and for impact case 1 in is able to keep the car always within the lane.

Tables 7.7 and 7.8 displays the comparisons at Y_{max} for impact case 1 and 2 respectively.

Table 7.7: Clinic performance at Y_{max} comparison for impact case 1

	PISC off	PISC on	With PISC
Y_{max} [m]	3.16	1.43	Better
Longitudinal velocity [km/h]	23.04	70.62	Worse
Lateral velocity [km/h]	-0.33	-1.07	Better
Yaw angle [°]	-34.69	-23.48	Better
Side slip angle [°]	33.85	22.59	Better
Yaw rate [°/s]	-14.50	-41.01	Worse

Table 7.8: Clinic performance at Y_{max} comparison for impact case 2

	PISC off	PISC on	With PISC
Y_{max} [m]	9.52	3.17	Better
Longitudinal velocity [km/h]	2.58	70.04	Worse
Lateral velocity [km/h]	-0.06	-0.82	Better
Yaw angle [°]	141.79	-13.18	Better
Side slip angle [°]	-60.30	12.51	Better
Yaw rate [°/s]	3.32	-37.58	Worse

The overall trend is that PISC reduces Y_{max}, yaw angle and side slip angle while the longitudinal velocity and yaw rate increases and the lateral velocity, naturally, only deviates slightly.

This is expected since the function uses both steering and braking to try to minimise lateral deviation and keep the car facing forward in the minimum amount of time some it might increase the yaw rate by abruptly trying to face the direction opposite to the lateral movement.

The results described can be clearly seen by analysing the paths for each impact case both with and without PISC. These paths can be seen in figures 7.1 and 7.2.

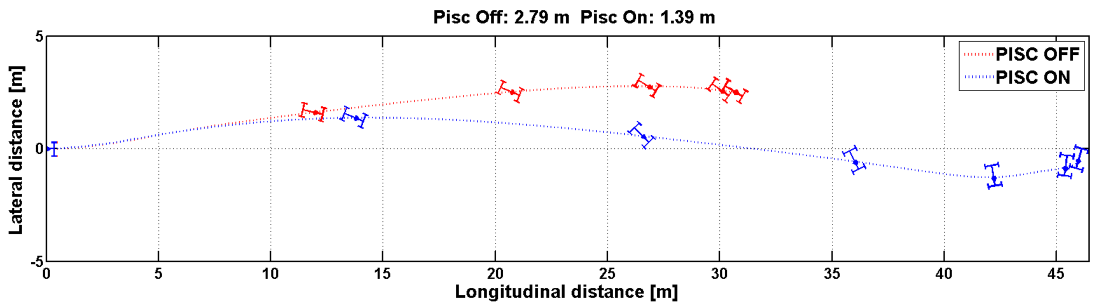

Figure 7.1: *Example of one path plot for impact case 1*

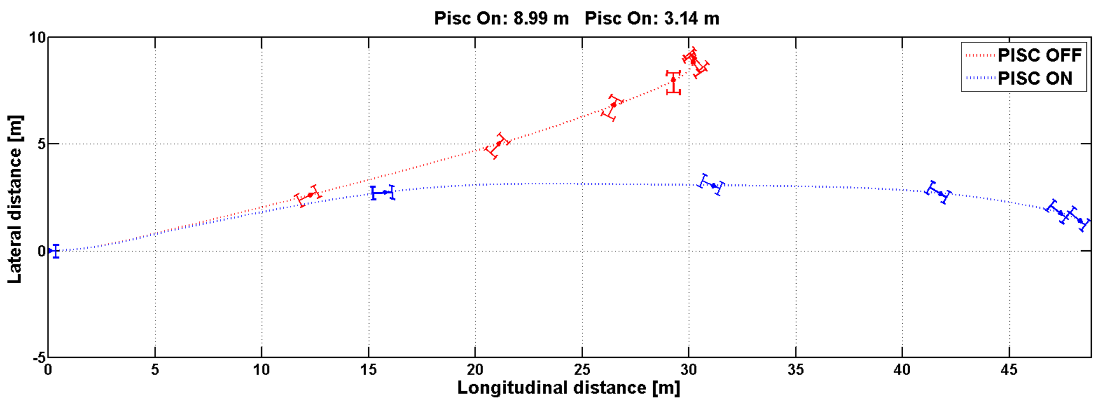

Figure 7.2: *Example of one path plot for impact case 2*

From both figures an overall improvement can be seen as expected from the functioning of the PISC function.

7.2.1 Test case 24

Test case 24 as mentioned in the previous chapter was an outlier in regards to Y_{max}. This occurs because the PISC function never disengages because the lateral speed, variable that is used to determine that Y_{max} is reached, never crosses 0. Therefore the PISC continues to be active and to try to minimise the lateral deviation of the car and ends up overcompensating for it.

This problem arises from using the way the function is disengaged. Since the global lateral speed is used and that one is determined from the double integration of the acceleration and the acceleration profile in this particular case might have caused the error and therefore generated the outlier.
One of the possible solutions for this problem is a local determination of the lateral speed or a reference shift at the moment of impact. Another possible solution is a more advanced method to estimate the lateral velocity from the production sensors.

8 Conclusions

The Post Impact Stability Control function is efficient in reducing the lateral deviation after impact, it will however increase the longitudinal distance travelled when compared to a case where only the PIB function is active. This happens because the PISC function tries to reduce the lateral deviation and not to reach a complete stop. Moreover the PISC function also reduces the yaw angle when compared to a case with only PIB. This is a more desirable vehicle orientation after impact when striving to mitigate the severity of a potential secondary impact.

The PISC function leads to high yaw rates which could be prejudicial after the function disengages since the driver might not be able to regain control of the vehicle. The high longitudinal speed might also affect the drivers' performance after Y_{max} is reached.

Overall the PISC function works as predicted but the usage of the PIB function as a settling controller might not be enough due to the high yaw rate combined with a high longitudinal speed.

A way of calculating steering feedback torque from the suggested PISC steering was developed and prepared for future implementation.

According to most test subjects the lack of steering feedback, motion and peripheral vision affect seriously the overall driving feel. This was expected and understandable and was deemed not to affect the main goal of the thesis although it might have some influence in the results.

The steering arbitration was tested offline, however the results show that this concept could be used and implemented online.

9 Future work

The future work suggestions can be divided into three major areas; platform performance, model behaviour and controller performance.

The main flaws in the platform performance is:

- Broken steering feedback motor
- Malfunctioning motion platform
- Huge backlash in steering column

The steering feedback problem could be fixed by just replacing the relevant motor, whereas fixing the malfunctioning motion platform would probably require the entire platform to be disassembled and all moving parts cleaned from dust and debris and re-lubricated. The steering column currently implements at least two universal joints, removing at least one of them would most likely reduce the backlash.

The primary areas in need of improvement in the regulator are:

- More comprehensive settling controller
- Online tuning of PISC parameter
- Local determination of $Ymax$

The current settling controller is the PIB function which only tries to stop the car as fast as possible. A settling controller that tried to reduce the yaw rate generated by the PISC function and to keep the heading would be preferable.

The PISC parameter was tested and tuned offline because the tuning parameter depends on the post impact states. A method for the online determination of the tuning parameter should be developed.

The Ymax is determined by the global lateral speed. As it was shown it is reliable for most cases but can for some particular situations prevent the disengaging of the function. A method more reliable method to determine the Ymax could be subject of an investigation.

The steering arbitration needs to be improved in order to be used in vehicles with EPAS, hence not steer-by-wire. Ways to detect if the driver is letting himself be guided or not and how to detect when he is fighting the system.

Another issue regarding not directly the PISC function but the general simulator driving feel is the engine sound feedback. Since the gear box modelling consists of a look up table it leads to static jumps in rpm. Since the rpm directly determines the engine sounds that are played back to the driver this leads to a quite unrealistic experience sound-wise. A solution would be to have a more dynamical model of the gearbox.

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A PISC function

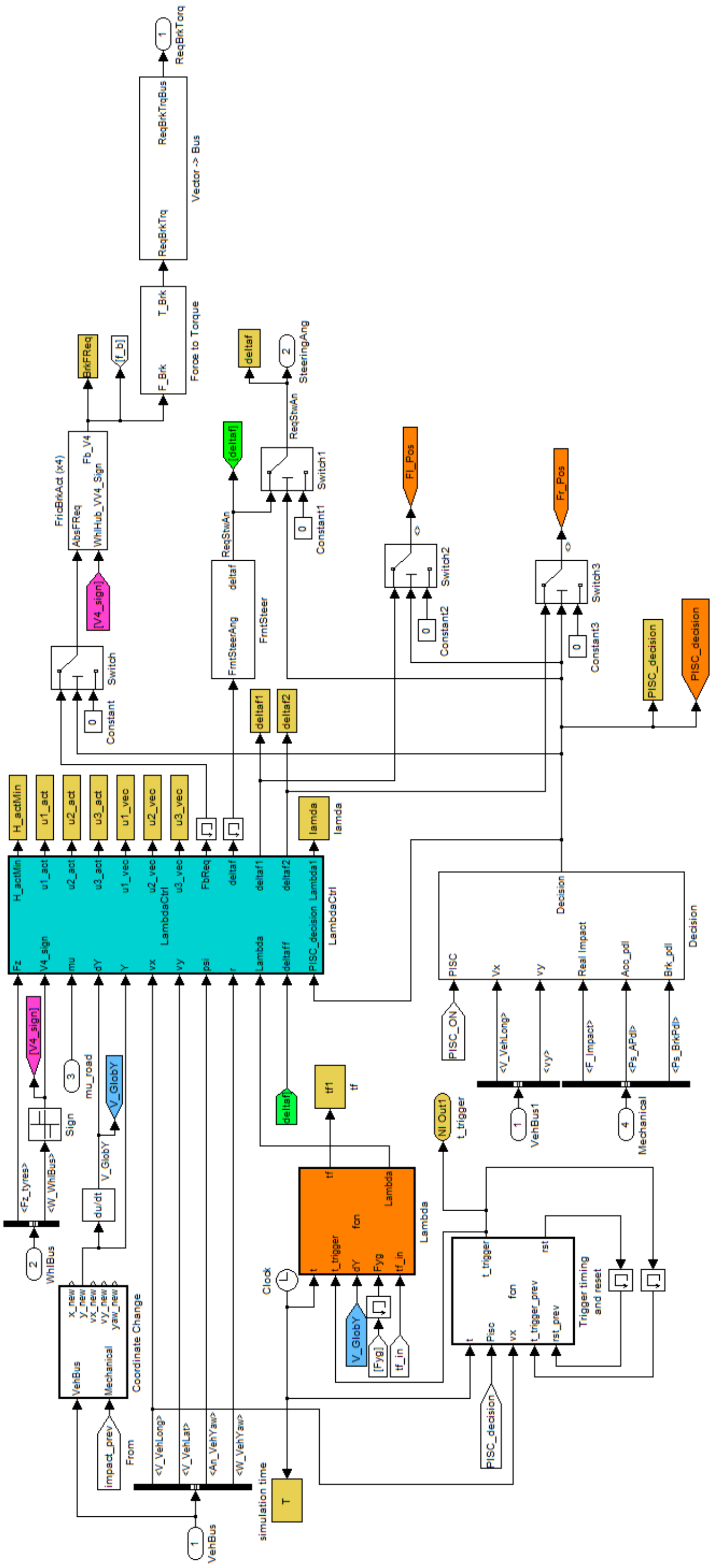

Figure A.1: *Simulink PISC function block*

B Questionnaire

Questionnaire

Name: ____

Test case #: __________

Gender:_____

Questions:

1. Was the experiment annoying or stressful (from 0 to 10)?

2. Can you describe briefly the unusual events?

3. How realistic did you find the simulator (from 0 to 10)?

4. Would you have reacted differently in a real-world situation?

5. Are you satisfied with your reaction on the impact?

6. Are you satisfied with your reaction time?

7. Did you notice any driver assist function after the impact?

8. If yes:
   a) In which way this function helped you and in which case?

   b) If you knew about the existance of the function, would you react differently?

9. Would this experience help you if this happen to you in real life?

Figure B.1: *Clinic questionnaire*