

Institutionen för systemteknik

Department of Electrical Engineering

Examensarbete

Steering System Verification Using Hardware-in-the-Loop

Examensarbete utfört i Fordonssystem
vid Tekniska högskolan vid Linköpings universitet
av

Salko Bjelevac och Peter Karlsson

LiTH-ISY-EX-15/4831-SE

Linköping 2015



Linköpings universitet
TEKNISKA HÖGSKOLAN

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Linköping, 12 juni 2015

	Avdelning, Institution Division, Department Avdelningen för Fordonssystem Department of Electrical Engineering SE-581 83 Linköping	Datum Date 2015-06-12
Språk Language <input type="checkbox"/> Svenska/Swedish <input checked="" type="checkbox"/> Engelska/English <input type="checkbox"/> _____	Rapporttyp Report category <input type="checkbox"/> Licentiatavhandling <input checked="" type="checkbox"/> Examensarbete <input type="checkbox"/> C-uppsats <input type="checkbox"/> D-uppsats <input type="checkbox"/> Övrig rapport <input type="checkbox"/> _____	ISBN _____ ISRN LiTH-ISY-EX-15/4831-SE Serietitel och serienummer ISSN Title of series, numbering _____
URL för elektronisk version http://urn.kb.se/resolve?urn=urn:nbn:se:liu:diva-119332		
Titel Verifiering av ett styrsystem genom Hardware-in-the-Loop Title Steering System Verification Using Hardware-in-the-Loop Författare Salko Bjelevac och Peter Karlsson Author		
Sammanfattning Abstract <p>In order for leading industrial companies to remain competitive, the process of product development constantly needs to improve. In order to shorten development time – that is the time from idea to product – simulations of products in-house is becoming a popular method. This method saves money and time since expensive prototypes become unnecessary. Today the calibration of steering gears is done in test vehicles by experienced test drivers. This is a time consuming process that is very costly because of expensive test vehicles.</p> <p>This report investigates possibilities and difficulties with transferring the calibrations from field to rig. A steering rig has been integrated with a car simulation program. Comparisons between simulation in the loop (SIL) and hardware in the loop (HIL) have been made and differences between different configurations of steering gears have been evaluated. An automatic process including calibration of parameters, testing and analysis of the test results has been implemented. The work laid the foundation of calibration of steering parameters and showed correlation between calibration parameters and objective metrics.</p>		
Nyckelord Keywords HIL, EPAS, steering system, electric power assisted steering, calibration		

Sammanfattning

Utvecklingen av produkter i dagens ledande industriföretag behöver gå allt snabbare för att möta konkurrensen. För att ligga i teknikens framkant behöver således nya metoder för produktutveckling anammas. För att förkorta ledtiden, det vill säga tiden från idé till färdigutvecklad produkt, görs allt mer arbete i simuleringar istället för att utveckla dyra prototyper. I dagsläget sker kalibrering av styrväxlar i testbilar med hjälp av erfarna testförare. Detta är en tidskrävande process som också är kostsam då testbilar är dyra.

I denna rapport undersöks möjligheter och svårigheter med att gå från kalibrering av styrväxelparametrar i testbilar till kalibrering i rigg. En rigg för testning av styrväxlar har integrerats med ett program för bilsimulering. Jämförelser mellan simulation-in-the-loop (SIL) och hardware-in-the-loop (HIL) har gjorts och skillnader för olika konfigurationer av styrväxlar, det vill säga olika hårdvara och olika mjukvara, har utvärderats. En automatiserad process innehållande kalibrering av parametrar, testning och analys av testresultat har implementerats. Arbetet har lagt grund för kalibrering av styrväxlar i styrriggen och visade samband mellan vissa kalibreringsparametrar och objektiva mätetal.

Abstract

In order for leading industrial companies to remain competitive, the process of product development constantly needs to improve. In order to shorten development time – that is the time from idea to product – simulations of products in-house is becoming a popular method. This method saves money and time since expensive prototypes become unnecessary. Today the calibration of steering gears is done in test vehicles by experienced test drivers. This is a time consuming process that is very costly because of expensive test vehicles.

This report investigates possibilities and difficulties with transferring the calibrations from field to rig. A steering rig has been integrated with a car simulation program. Comparisons between simulation in the loop (SIL) and hardware in the loop (HIL) have been made and differences between different configurations of steering gears have been evaluated. An automatic process including calibration of parameters, testing and analysis of the test results has been implemented. The work laid the foundation of calibration of steering parameters and showed correlation between calibration parameters and objective metrics.

Acknowledgments

We would like to thank our supervisor at Volvo, Matthijs Klomp for valueable input and good suggestions during our thesis work, without you none of this would have been achieved. Big thanks to Marcus Ljungberg at Volvo for his support and help throughout the project. Thanks to Diomidis Katzourakis at Volvo for his help, especially in the beginning of the project. Thanks to our supervisor at Linköping University, Kristoffer Lundahl, especially for help and input on this report. We would also like to thank our examiner Jan Åslund.

*Gothenburg, June 2015
Salko Bjelevac and Peter Karlsson*

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Notation

PARAMETERS AND VARIABLES

Notation	Betydelse
δ_H	Steering wheel angle
$drvMod$	Driving Mode (ECU-parameter)
F_{assist}	Assisted force (from the servo)
i_M	Electric motor current
M_{demand}	Demanded torque
M_E	Electric motor torque
$M_{E,ext}$	External electric motor torque
M_H	Steering wheel torque
M_L	Torque on belt
s_r	Steering rack displacement

ABBREVIATIONS

Abbreviation	Description
CAE	Computer-aided engineering
CAN	Controller area network
COM-API	Component object model - application programming interface
DOE	Design of experiment
ECU	Electronic control unit
EPAS	Electric power assisted steering
GUI	Graphical user interface
HIL	Hardware in the loop
I/O	Input/output
NVH	Noise, vibration and harshness
ISO	International Organization for Standardization
PC	Personal computer
PI	Proportional, integral (regulator)
PLC	Programmable logic controller
RTI	Run-time infrastructure
RTS	Real-time system
SIL	Simulation in the loop
TCP/IP	Transmission control protocol/internet protocol

1

Introduction

Volvo Car Corporation is a leading car company, following the new trend of product development by simulation. In order for Volvo to stay competitive, a goal called 202020 has been set. This focuses on shortening the development time for new car models to 20 months by the year 2020. In order to decrease development time, new product development methods need to be established. A trend among leading technical companies is to model the products and test them in simulations. A product that this development strategy could be applicable for is the steering system at Volvo, which today is mainly tested and tuned in complete vehicles by test drivers.

This master thesis work focuses on the implementation and validation of a steering system of a car, both in simulation-in-the-loop (SIL) and hardware-in-the-loop (HIL). In SIL, the system to be tested is simulated together with other systems; for example, if a steering system is to be tested in SIL, all other systems such as the braking system, the engine and so on are also modelled. In HIL, the tested system is the actual hardware, where all other systems are simulated. The thesis work is performed at Volvo Car Corporation, Gothenburg, Sweden.

1.1 Background

In the most recent Volvo vehicles the steering system employs electric power assisted steering (EPAS) for the steering assist. The purpose of the EPAS system is to assist the driver with extra force to the steering rack in order to decrease the steering wheel torque required by the driver. The electronic control functions of the EPAS system, located in the ECU of the steering gear, are calibrated to achieve desired characteristics of the steering. The desired characteristics are predefined

values of certain steering related objective metrics that are set by Volvo.

Volvo has recently bought a steering-rig from Silver-Atena with the purpose to move some of these field tests to simulations. The work presented in this thesis has been performed in and around this rig.

Today steering systems are mainly tested and tuned in complete vehicles by test drivers. This is a process which costs money and time [1, 2]. Another disadvantage with this approach is that it is difficult to guarantee continuity in the tests; this is due to differences in the driving and differences in the environment such as road imperfections and changing weather conditions. A new trend among technically leading companies is the increased usage of computer based simulations in the development of products. By moving the tests from the road to simulations in SIL and HIL, and replacing test drivers with computers, time for the testing can be minimized [1]. This would make the development of automobiles more effective, shorter lead times and thereby enhance the performance of them.

In contrast to field tests, the tests in simulations lacks the subjective feeling from an experienced test driver [3]. Due to this, the need of objective measurements that are well correlated with the subjective feeling are crucial in order to optimize the calibration process. Many studies on the topic of how to correlate the subjective feel of test drivers and objective metrics have been done. The first attempts were made back in the 70's but it is still a field of great interest [4].

Since simulations of this kind is a relatively new area of study (with specifying a maneuver, the road and so on) in a hardware rig, only a few studies on this subject have been done. Daimler AG has proposed an implementation of the software LabCar together with a HIL bench [1]. The main difference between their implementation and the one presented in this thesis work is the software that has been used.

At Kia, there has been a project where an EPAS system was implemented in order to perform HIL simulations. It was used to simulate driving scenarios and to find malfunctions. The EPAS was later installed in a car, indicating outstanding performance and therefore proven HIL testing is applicable for EPAS [5].

In a former thesis work at Volvo Cars in Gothenburg, an optimization of steering parameters was done in SIL, where it was shown that it was possible to get a better optimized steering employing computer aided-engineering (CAE) [6].

1.2 Problem Formulation

In order to increase the efficiency and decrease the development time of a new product, new development methods need to be established. This thesis work investigates the possibilities to cut development time for the steering system.

1.3 Purpose

The purpose with this thesis work was to show that a method of calibration, simulation, and analysis in a HIL rig could be used as a method to optimize objective metrics related to the steering performance. The analysis and verification part of the work would make it possible to verify and parameterize SIL models of steering systems better. This work is a proof of concept that shows that it is possible to use a HIL rig for this purpose after further development.

1.4 Method

The method of this thesis work can be divided into the following parts:

- To integrate Volvo's steering system and a new steering model with a car simulation program in order to be able to run simulations in SIL.
- To validate the new steering model by comparing results from simulations of it with simulations from Volvo's steering system. This is performed in SIL.
- To integrate Volvo's steering-rig with a car simulation program and to be able to perform tests specified in the car simulation program in HIL.
- To automatize the complete calibration process that includes calibration of ECU parameters, testing and analysis of testing results.
- Perform a sensitivity analysis and investigate how certain parameters and combination of parameters affect the metrics, which in turn affect the desired steering performance. It is important to have in mind that the sensitivity analysis is only an example, a proof of concept, and is not destined to be used for product development.

1.5 Thesis Outline

The outline of this report is as follows:

- **Chapter 2 - Preliminaries**
This chapter gives an introduction to the functionality and modeling of steering system and explains how it is constructed.
- **Chapter 3 - Steering Rig**
The steering rig chapter explains everything related to the steering-rig; which components it consists of and how it operates.
- **Chapter 4 - Implementation**
This chapter thoroughly explains the integration of the rig with CarMaker and all the steps of the automatized process, which is calibration, simulation, and analysis.

- **Chapter 5 - Results**

In chapter 5 the results are presented and a discussion is held.

- **Chapter 6 - Conclusions and Further Work**

In this chapter, conclusions are drawn and the possibilities and future work of the project is discussed.

2

Preliminaries

The following chapter describes the steering models that are used throughout this report. Focus is put on the Pfeffer steering model [7], which is a model in CarMaker, and the reason for the usage of this model is to compare it with Volvo's and see how well they match. Volvo's steering model has been used as much as the Pfeffer model but is not described in detail because of professional secrecy. The fact that Volvo's model is not described in this document is not an issue for the reader since the differences in performance between the two models are not essential, which is shown in Section 5.1.1.

2.1 Introduction to the Power Assisted Steering System

Before power steering systems were introduced, larger steering wheels were used, in order to make it possible for the driver to deliver the required steering torque. Today different power assisted steering systems exist, such as hydraulic systems, electric systems and hydraulic-electric systems. There are several advantages in an EPAS system compared to a hydraulic steering system. The servo motor efficiency is better which leads to better fuel economy [8]. Another advantage is the simplicity of the EPAS; the hydraulic system has several components such as a pump, a belt to drive the pump, fluid to transfer the energy from the pump to the steering gear and these components can be eliminated by using an EPAS.

The steering system consists of the following components: input shaft, torsion bar, ECU and motor, servo gear, ball nut gear and rack. Figure 2.1 shows the complete mechanical steering system, without power-steering.

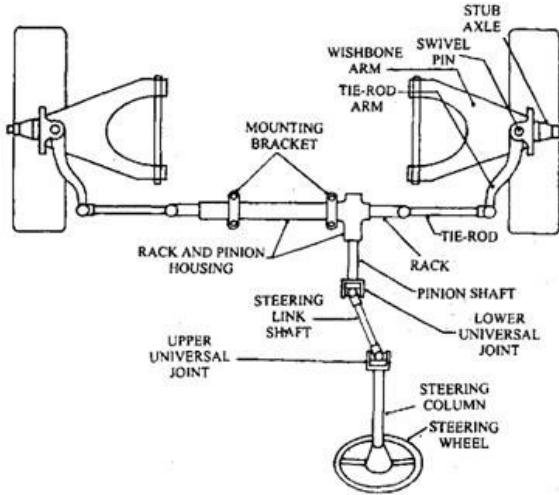


Figure 2.1: Schematic figure of how the steering system is connected to the wheels [9].

The function of the steering system is that the driver applies a torque to the steering wheel, which is connected to the steering column. The steering column is connected to the pinion shaft via the upper and lower joint and the steering link shaft. The torsion bar, called the pinion shaft in Figure 2.1, transmits the torque to a force on the steering rack. This causes the tie rods to move and the wheel angles to change.

The steering gear used in this thesis work is of the electric type. There are three types of electric powered steering gears, with different positioning of the servo unit, and these are the following: servo unit on the steering column, servo unit on a second pinion and paraxial servo unit. The different properties of the steering gears are that they can apply different amounts of force/torque in different ways. The best choice of steering gear depend on the weight of the car. The heavier the car, the more assisted force it needs and the price increases. The steering gear with paraxial servo unit has been used in this thesis work, since the simulations has been done for the steering system of the XC90 which is considered a heavy car. The different configurations can be seen in Figures 2.2-2.4.

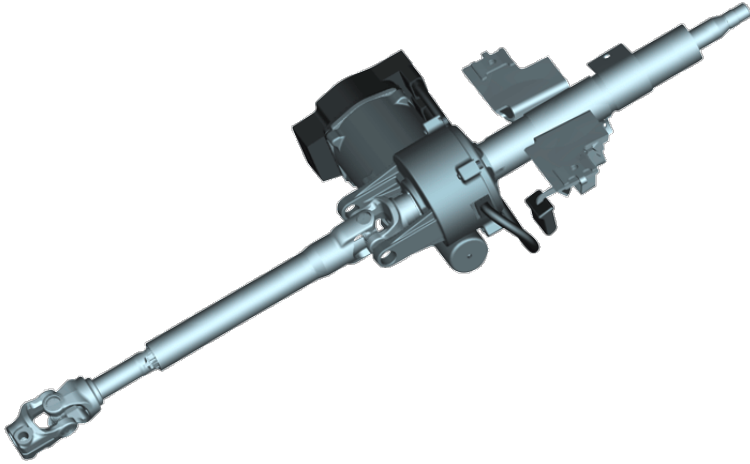


Figure 2.2: Column mounted servo (EPSc). Used for steering axle loads up to 1000 kg [10].

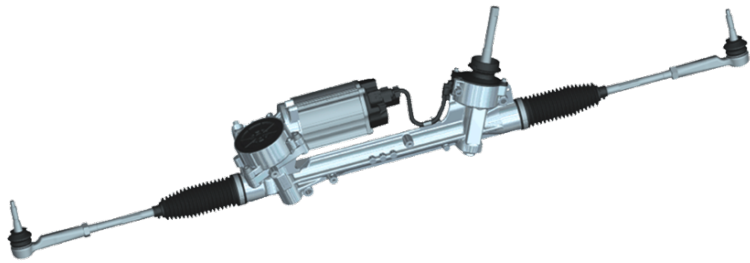


Figure 2.3: Servo mounted on second pinion (EPSc). Used for steering axle loads up to 1200 kg [10].

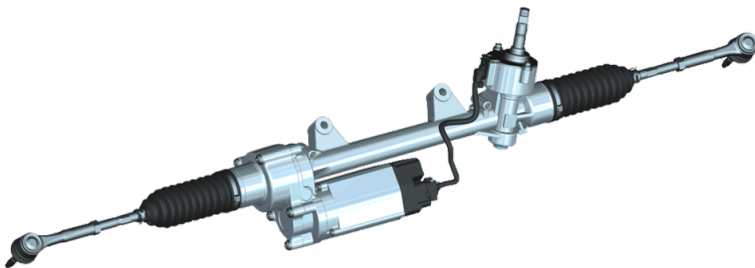


Figure 2.4: Paraxial mounted servo (EPSapa). Used for steering axle loads up to 1600 kg [10].

2.2 The Pfeffer Model - The Mechanical Module

The mechanical parts of a steering system, from the steering-wheel to the steering rack, are described in this section. Figure 2.5 shows the mechanical structure of the Pfeffer steering module [7]. A torque M_H or an angle δ_H is applied at the steering-wheel and can be seen as the input signal of the system. The steering-wheel is attached to the steering column which in turn is coupled with the torsion bar. The torque and angular displacement of the steering-wheel is transferred to the steering rack via the steering column, torsion bar, and finally the column. The steering rack displacement s_R is the output signal of the system and the steering rack itself is attached to the wheel suspension.

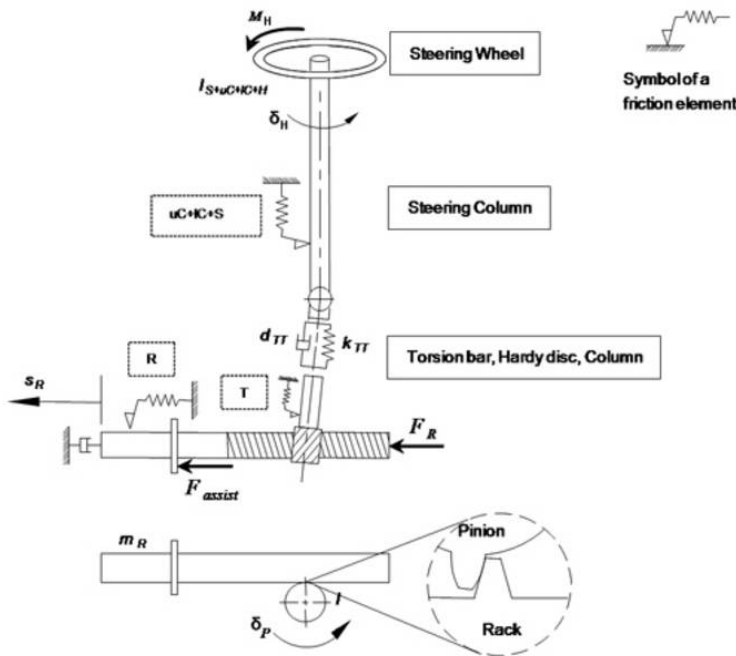


Figure 2.5: The mechanical structure of the Pfeffer steering model including forces, parameters and other signals of importance [7].

2.3 The Pfeffer Model - Power Assistance Module

The power assistance module is a module that reduces the required steering power from the driver by applying external force or torque. It consists of a servo motor and an electronic control unit (ECU) which controls the motor. There are several types of power assistance modules such as hydraulic (HPA) and electric (EPSc and EPSapa) ones. EPSc uses an electric motor coupled to the steering column or to a second pinion, while the electric motor in EPSapa is coupled di-

rectly to the steering rack, see Figures 2.2-2.4. As mentioned, the EPSapa is the type that has been used in this thesis work. Since the electric motor is coupled directly to the steering rack in EPSapa, it applies the force F_{assist} there, as seen in Figure 2.5.

The EPSapa uses a PI-controller and it consists of a feedback loop which takes the difference between the demanded torque, M_{demand} , and the torque on the belt, M_L as input and gives the input to the electric motor current i_M as output. M_L is the sum of the torque produced by the electric motor torque M_E , and the external torque, $M_{E_{ext}}$. Note that a non-zero $M_{E_{ext}}$ would provoke a decline in i_M . The output of the complete system is M_L , which acts on the belt that is coupled to the steering rack, as described in Section 2.3. The control scheme can be seen in Figure 2.6.

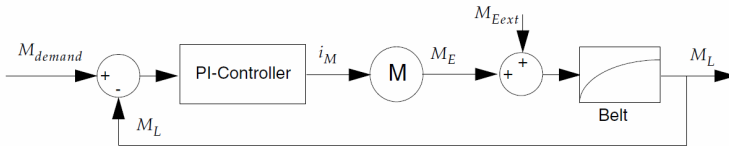


Figure 2.6: The structure of the control scheme for the EPSapa used in the Pfeffer steering model.

2.4 CarMaker

CarMaker is a program developed by IPG Automotive GmbH and is used for simulations of driving maneuvers. One can specify the maneuvers, the road and parameterize all components of a vehicle; for example tires, steering, driveline and engine can be chosen as generic models or one of your own choice. An advantage with CarMaker is that it uses look-up tables for most of the simulations, which makes simulations as fast as several times real-time.

CarMaker parameterizes the dynamic properties of the car, which is a Volvo XC90. In the SIL case, all parts of the car are modeled in CarMaker/Simulink but in the HIL case, the steering system is the actual hardware and is therefore not modeled. In the HIL case, CarMaker gives the required input signals to the rig: steering wheel angle and tie rod forces. CarMaker takes the rack displacement, the rack velocity and the rack acceleration as input from the rig.

2.4.1 CarMaker for Simulink

CarMaker for Simulink allows the user to modify existing software models in Simulink in order to change the behavior or performance of the car [11].

Figure 2.7 shows the "Car and Trailer" subsystem of the CarMaker for Simulink block. This block contains subsystems such as steering, kinematics and forces. In

this work, the steering block has been replaced by Volvo's steering block for SIL.

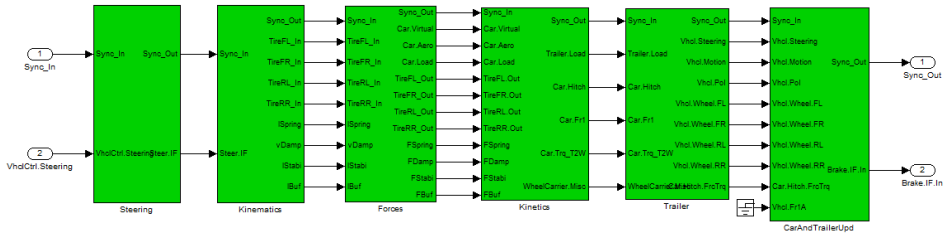


Figure 2.7: "Car and Trailer" subsystem of the Simulink model in CarMaker, where the steering block is replaced with Volvo's own.

2.4.2 Coordinate System in CarMaker

CarMaker uses a right handed cartesian coordinate system, which is important to know since the steering rig uses a different cartesian coordinate system.

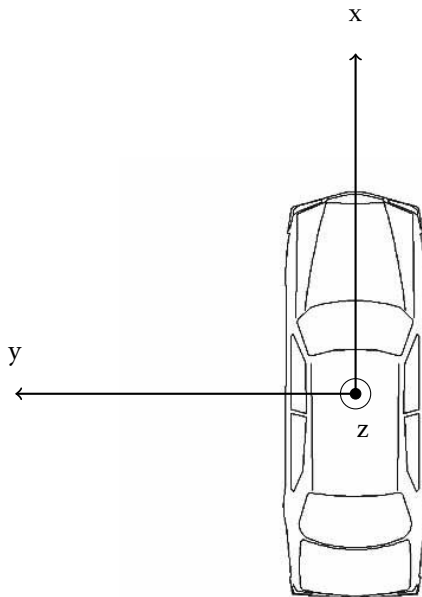


Figure 2.8: Coordinate system used in CarMaker.

3

Steering Rig

The rig for the HIL-testing of the steering system is manufactured by Silver Atena and was originally planned to be used for durability testing and noise vibration and harshness (NVH) testing. However an idea of integrating the steering rig to CarMaker was born at Volvo, which is the origin of the thesis work.

The rig system consists of the steering rig itself, a control cabinet with a real-time environment and a PC. Figure 3.1 is a schematic picture of the complete steering rig system and gives an overview of the belonging hardware and connections.

3.1 Overview of the Rig System

The steering rig consists of three actuators, and an electric power assisted steering (EPAS). The actuators are two linear drives that apply force on the steering rack directly and one steering robot that controls the steering by applying angle or torque to the steering column. The EPAS consists of an electronic control unit (ECU) and a servo motor with a gear coupling to the steering rack.

The steering gear to be tested is attached to the steering rig as can be seen in Figure 3.1. The forces and torque acting on the steering gear are shown in Figure 3.2, where the green arrows are forces or torque that act on the steering gear. The torque/angle of the steering wheel is eventually transmitted to the input shaft. The tie rod forces act on the left and right front wheels. The last force is the assisted force applied by the servo.

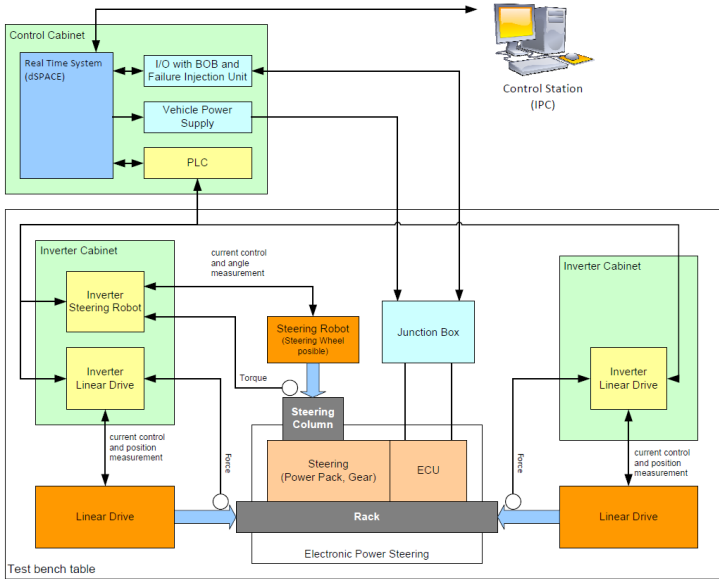


Figure 3.1: A schematic picture of the steering rig [12].

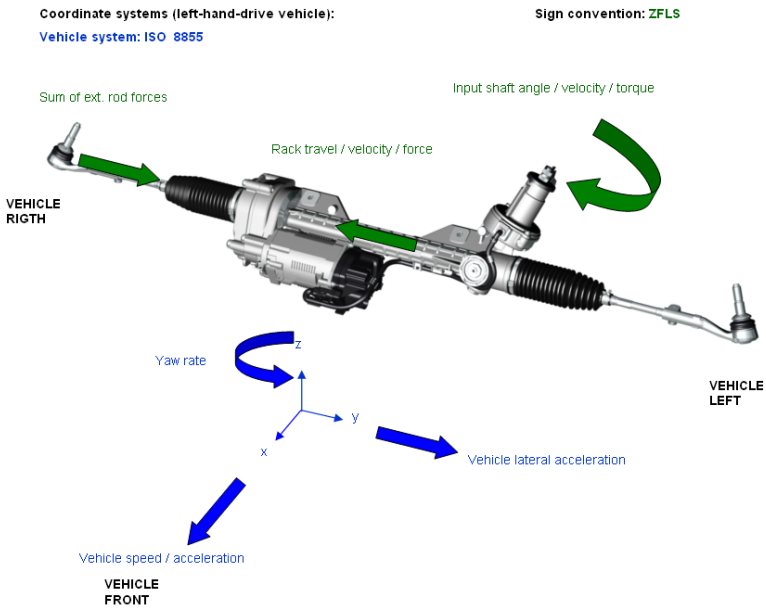


Figure 3.2: Picture of an EPAS with relevant forces, torques and coordinate system[13].

3.2 Coordinate System of the Rig

The rig uses a coordinate system where counter-clockwise angle is positive and rack displacement is positive to the right, see Figure 3.3.

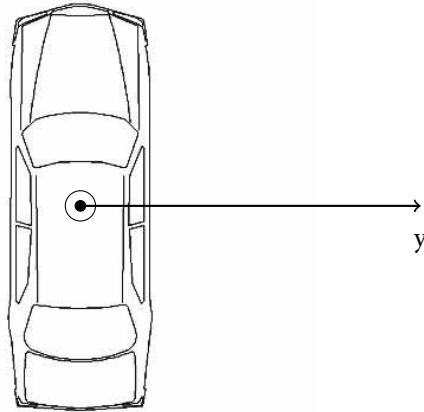


Figure 3.3: The coordinate system of the rig, using same notation as in Figure 2.8.

3.3 Hardware

The steering rig consists of three actuators and an EPAS. The two linear actuators apply the simulated tie rod forces to the steering gear and are located at each side of it. The steering robot simulates the driver and is attached to the steering column and applies angle or torque to it. The EPAS consists of an ECU and a servo motor with a gear coupling to the steering rack [12].

3.4 Software

As can be seen in Figure 3.1 there is a control station, which is a PC, running software in order to communicate with the real-time system dSpace. The operative system of the PC is Windows 7 and the programs associated with the steering rig are dSpace AutomationDesk and dSpace ControlDesk.

AutomationDesk is used to implement test sequences and ControlDesk is used to control the real-time simulation and to download the software to dSpace.

3.4.1 dSpace

The real-time system (RTS) used in the rig is dSpace, which the software mentioned in Section 3.4 communicate with. The dSpace system is mostly used to simulate vehicle models and to send target values to the programmable logic controller (PLC).

3.4.2 PLC

The programmable logic controller (PLC) is used to control the states for the steering robot, the left wheel actuator and the right wheel actuator. It also checks if dSpace receives CAN-data from the rig. Another important task it has is to compare measurements with user defined safety limits and shut down the system in case of overshoot. All three actuators are controlled by PI-controllers with a feedforward bypass.

3.5 Communication and Control

The communication of the steering rig consists of an optic cable that is connected between the PC and dSpace, a CAN-bus between dSpace and the ECU and the actuators. A schematic picture of the connections can be seen in Figure 3.1.

3.5.1 CAN

The control area network (CAN) that is used connects the dSpace system with the PLC. It consists of four channels; one is used for communication with the ECU and the other three are used for sending data to the motion controllers and receiving measured data from the sensors.

3.5.2 GUI

The graphical user interface (GUI) is the ControlDesk, installed on the PC, which in turn is connected to dSpace via an optical cable. The GUI is used to control the system and lets the user set parameters and perform tests. The GUI is also used for surveillance of ongoing tests.

3.5.3 Control

The systems to be controlled are the steering robot and the two linear drives. The control signal for the steering robot is either the steering wheel torque or the steering wheel angle. It is a closed loop with the rack displacement, rack velocity and rack acceleration as feedback signals. The two linear drives to be controlled simulate the external tie rod forces and therefore takes them as input signals. The tie rod forces depend on several parameters such as steering wheel angle, vehicle speed and external forces such as road friction and wind.

The three actuators also have an internal control loop that is controlled by the PLC as mentioned previously.

4

Implementation

This chapter describes the complete process of calibration, simulation, and analysis. To be able to simulate a variety of different ECU parameter values and combinations of parameter values in a smooth way, the whole process has been automated.

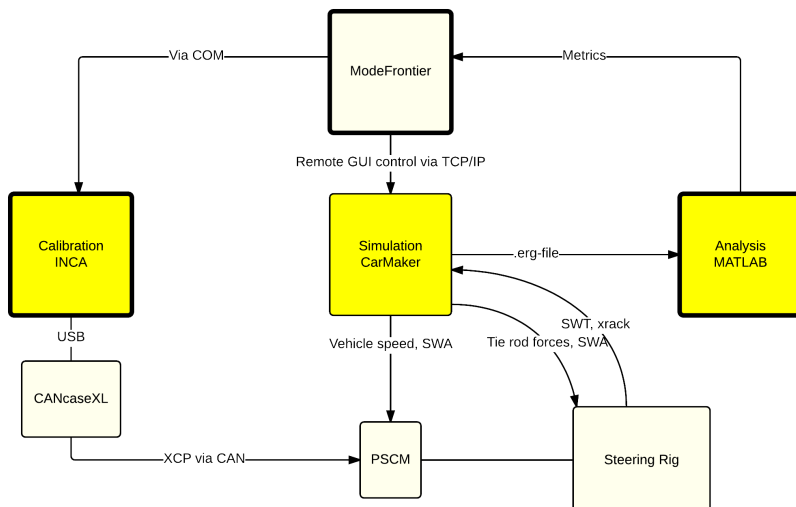


Figure 4.1: Schematic figure over the automated process. The bolded boxes represent tasks performed on a laptop. The yellow boxes represent the main tasks that are done in the automated process.

Figure 4.1 gives an overview of the complete automation process. First a calibration of the desired ECU parameters is done. Then a simulation of a driving scenario is run, which gives a result file. This is imported into a post-processing script, which gives the metrics. The procedure is then repeated for different ECU parameter configurations.

4.1 Integration of the Rig with CarMaker

The overview of the integration can be seen in Figure 4.2, where a simplified flowchart is illustrated. The middle block is exchanged depending on if the simulations are performed in HIL or SIL. In HIL, the steering rig is used and in SIL, a Simulink model of the steering system is used.

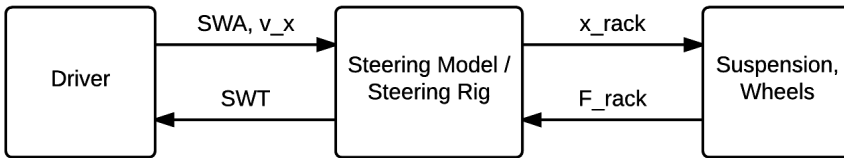


Figure 4.2: Simplified integration overview. The driver is simulated in CarMaker and interacts with either the steering rig or a steering model in Simulink.

In order to integrate the steering rig with the steering gear and CarMaker, a closed loop of signals has been created. The inputs to the steering rig are the steering wheel angle and the tie rod forces and they are simulated in CarMaker. The inputs to the ECU are the car velocity from CarMaker and the steering wheel angle obtained from measurements in the rig. The position, velocity and acceleration of the steering rack, together with the steering wheel torque are fed back into CarMaker. This process is depicted in Figure 4.3

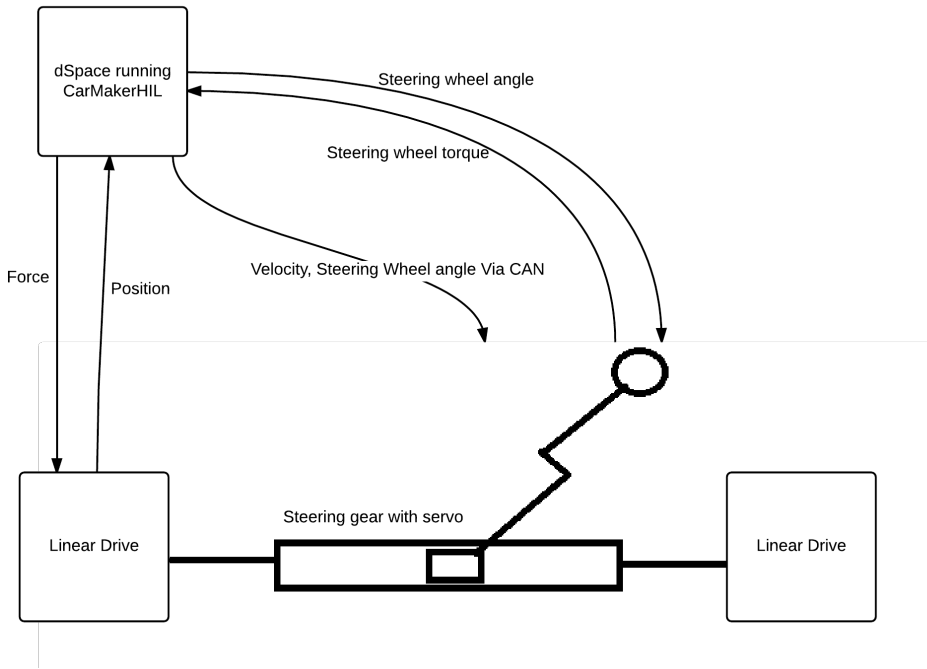


Figure 4.3: Simplified schematic of the steering rig setup.

dSpace is running C-code which is built by a Simulink model, where modifications can be made for example to integrate it with CarMaker. Figure 4.4 shows the top view of the rig's Simulink model together with CarMaker Simulink blocks. The input-output (IO) subsystem is used to transfer from and to raw values that are required by the hardware. It is in the subsystem MDL all modifications have been done.

A more detailed overview of the subsystem MDL is shown in Figure 4.5. It consists of the blocks MainControl, Vehicle, Drives and DataAcquisition. MainControl controls the operating mode of the steering rig and contains functions for test automation control. The vehicle block consists of bus simulation and vehicle control (engine speed and vehicle speed). The subsystem Drives is used to control the steering robot and both linear drives. DataAcquisition is used to filter and calculate various statistic values of measured signals and those provided by hardware interface.

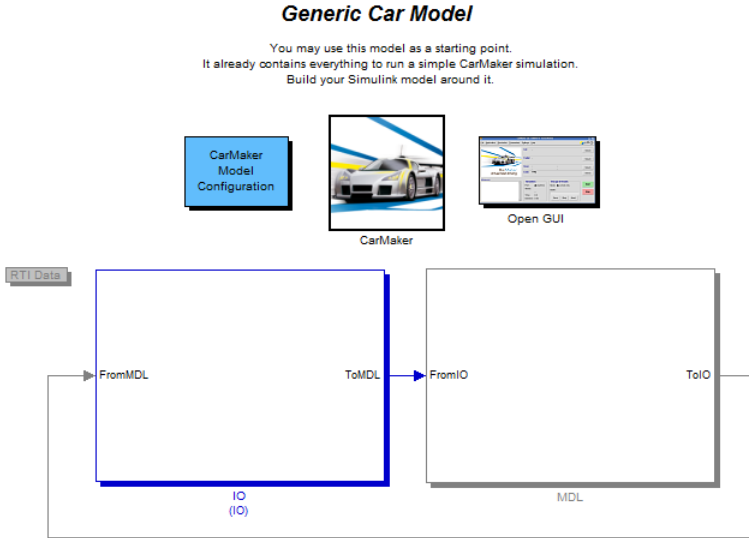


Figure 4.4: The top view of the Simulink block diagram of the rig together with CarMaker blocks. The three blocks at the top belong to CarMaker and the two big blocks belong to the steering rig.

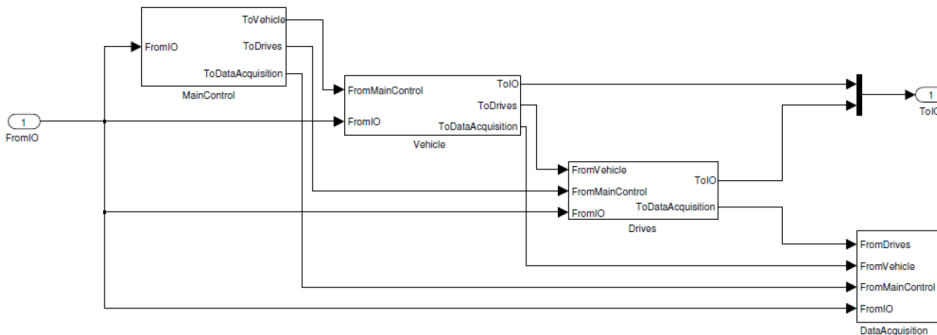


Figure 4.5: The MDL subsystem and its four main blocks.

Under the Vehicle block, the demanded angle and the tie rod forces from CarMaker are integrated and used as inputs to the rig. The demanded angle is multiplied with $\frac{180}{\pi}$ to transform it from radians to degrees, since CarMaker uses SI units. Both tie rod forces are multiplied with -1 because of differences in the coordinate systems of the rig and CarMaker, see Section 2.8 and 3.3. Figure 4.6 shows the connection with the CarMaker input signals.

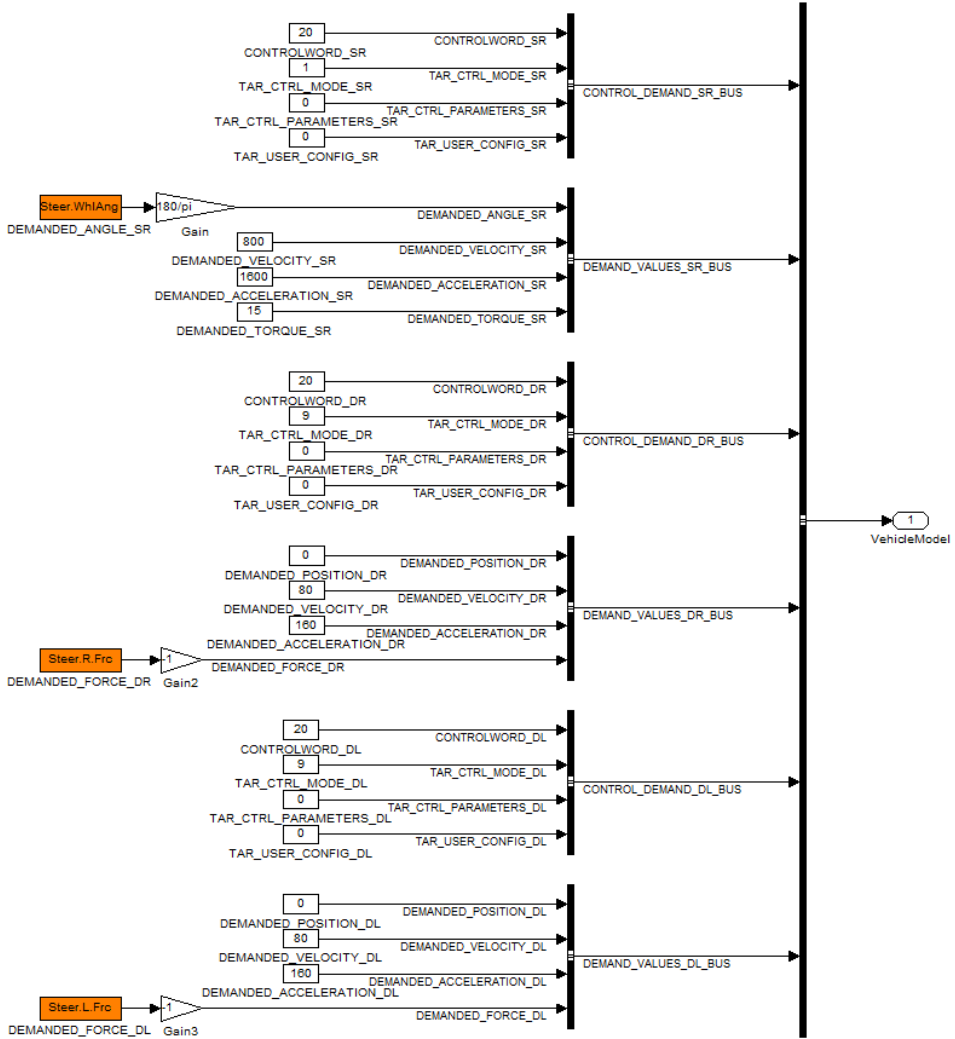


Figure 4.6: The vehicle model subsystem where CarMaker signals are used as input. The orange blocks are the simulated CarMaker signals demanded angle, tie rod force left and tie rod force right.

In the block "DataAcquisition", measured data from the rig is collected. The rack displacement and rack velocity that are measured in the rig are inputs to CarMaker. Measured data such as the steering wheel angle and the steering wheel torque from the rig are also collected in this block. The fact that the rig measures in millimeters and CarMaker measures in meters and also the coordinate systems difference result in that the gains of $\frac{-1}{1000}$ are used. Figure 4.7 shows the subsystem DataAcquisition with the output signals to CarMaker.

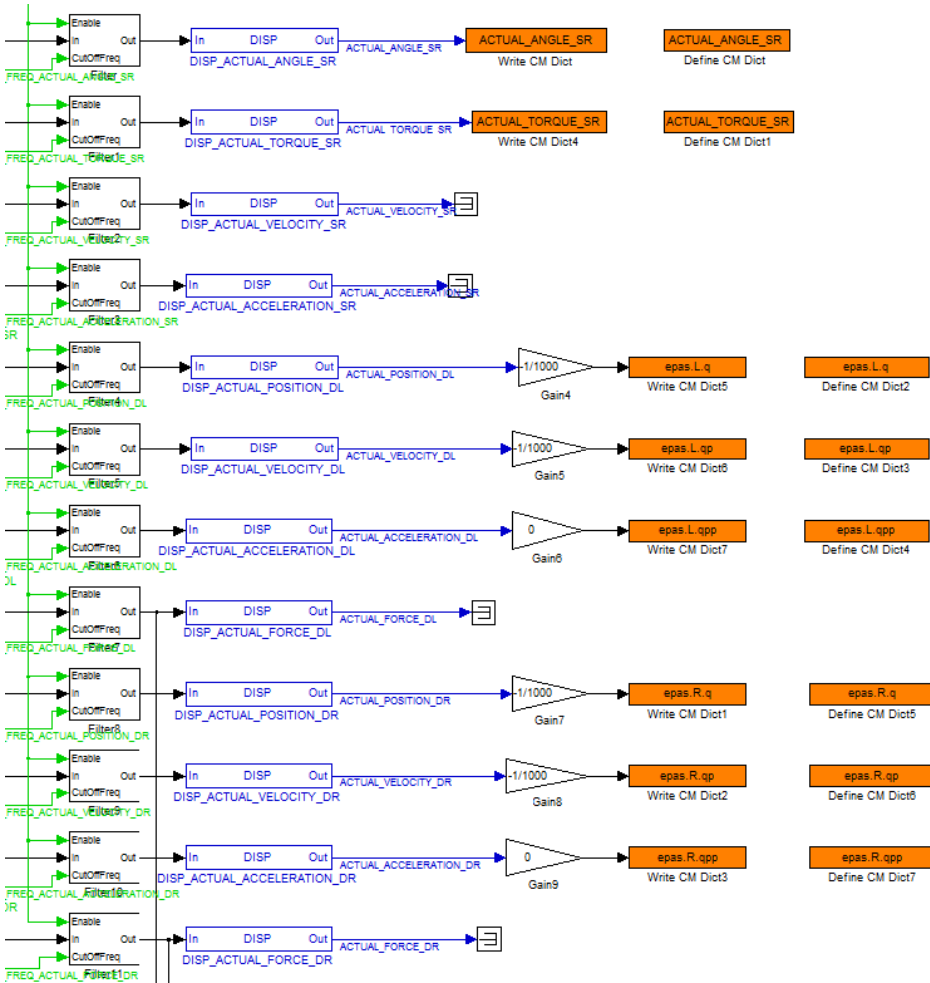


Figure 4.7: A selection of the DataAcquisition subsystem where the measured signals from the steering rig are taken as outputs.

The signals that are taken into CarMaker from the rig are then fed back into the CarMaker-model, which closes the loop. Figure 4.8 shows the steering system with the rack displacement and rack velocity taken from the rig instead of CarMaker.

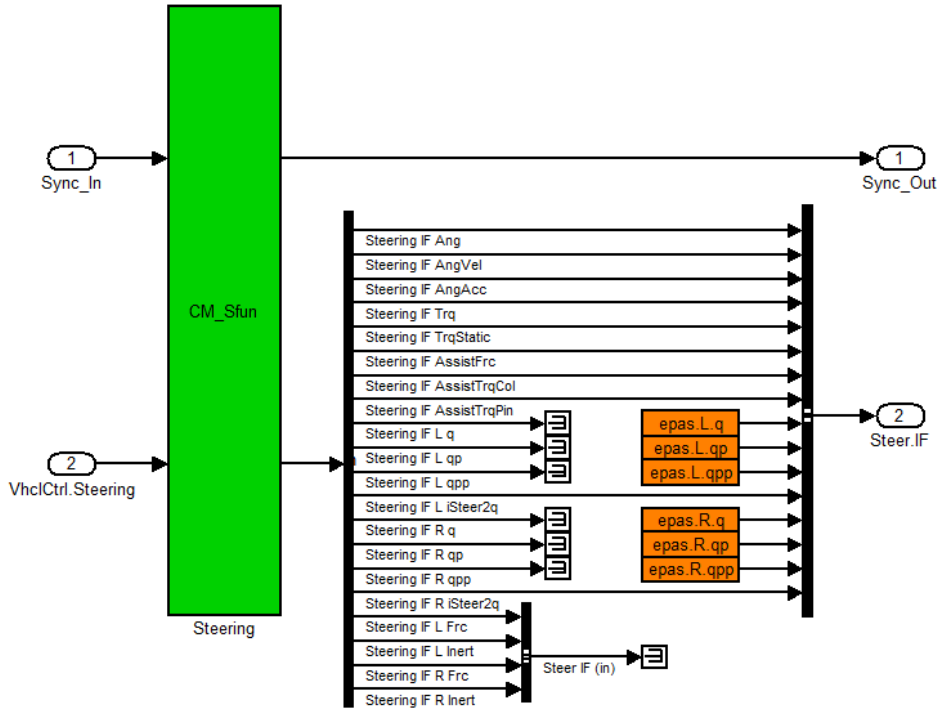


Figure 4.8: The steering subsystem where the internal CarMaker signals are terminated and replaced with the ones from the rig.

4.2 Calibration

The calibration of the ECU of the steering gear is a central part of this project. The parameters of the ECU are tuned in order to improve steering characteristics and to fulfill the demanded values on the related objective metrics. The calibrations are performed in INCA, where parameter values can be calibrated and visualized in real-time. INCA is installed on a PC and is controlled from a Visual Basic-script.

4.2.1 Setup

The PC on which INCA is installed is connected to an adapter from Vector GmbH called CANCaseXL via USB. The CANCaseXL is then connected to the dSpace Real-Time Interface (RTI) via a serial port (COM) and allows INCA to communicate with dSpace via CAN. This setup makes it possible for INCA to communicate, that is to read measured variables of the steering rig and calibrate parameters of the ECU. A flowchart describing the setup can be seen in Figure 4.9.

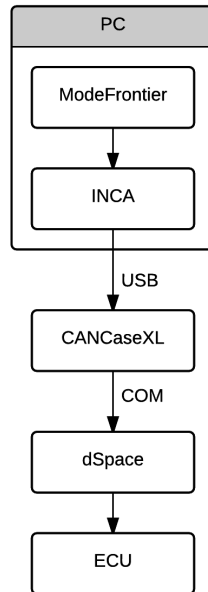


Figure 4.9: Flowchart describing every step of connections between the PC and the ECU.

To be able to perform automatized tests without supervision, INCA needs to be controlled by an external program, which in this case is ModeFrontier, see Section 4.5.

4.2.2 Process of Calibration

In order to be able to automatize the calibration process, the calibrations in INCA need to be controlled by another application. This can be done in different ways, for example using Windows COM-API (application programming interfaces) or from within CarMaker's script control.

In this thesis work, the chosen path is as mentioned to control INCA from a Visual Basic-script that runs from ModeFrontier.

4.2.3 Tuning of ECU Parameters

The ECU of the steering gear controls the servo, which affects the characteristics of the steering of the car. Numerous steering related parameters are included in the ECU and to obtain the desired performance, the different parameters need to be calibrated. An example of a very important set of parameters are the boost curves.

A boost curve is a function that determines how much assisted force the servo

should apply based on the torque generated by the driver and the velocity of the car. In CarMaker, the horizontal axis is torsion bar torque (the driver's torque is measured at the torsion bar) and the vertical axis is current (which multiplied with a motor constant gives the assisted torque). See Figure 4.10.

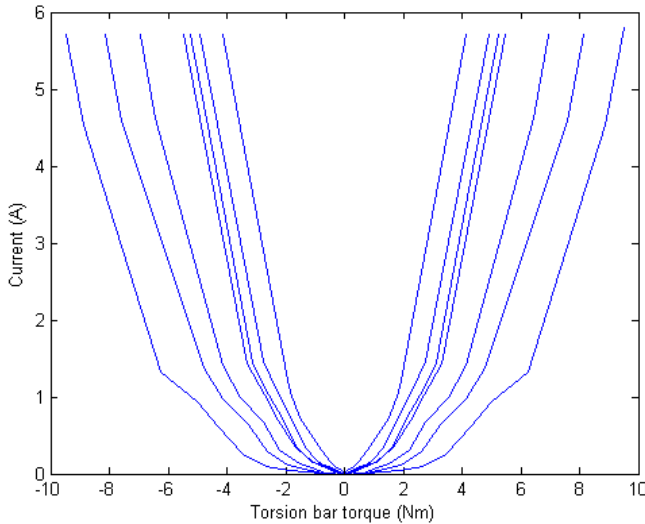


Figure 4.10: An example of boost curves, in this case the ones used in CarMaker. Each curve represents a vehicle speed. The lowest speed is the inmost curve.

In the system used by Volvo, the boost curves are relations between the steering wheel torque and the desired steering rack force, and decide how much assisted force the servo should apply to the steering rack in order to achieve desired steering rack force.

The principle is that the lower the vehicle speed is, the less steering wheel torque should be needed in order to get full rack force. This is desired when parking and jogging.

The manufacturer of the ECU software does not provide a direct way to calibrate the boost curves and therefore other parameters that affect the steering characteristics have been modified.

Important parameters that are calibrated in order to affect the steering performance, and thereby the metrics, are:

- **Active Return:** The active return curves in the ECU of the steering gear determine the steering wheel velocity depending on the steering wheel angle. The active return functionality applies a torque opposite to the steering

wheel torque, in order to return the steering wheel angle to 0° . This functionality can be seen when the driver releases the steering wheel and the steering wheel slowly returns to 0° .

- **Drive Mode:** A parameter that determines the amount of assisted force that is to be applied by the servo on the steering rack. It has three states, low, medium and high, that determine how much assisted force that should be applied in general. The drive mode is also called the personalization, since different drivers prefer different drive modes.
- **Velocity:** A dummy speed is sent to the ECU in order to trick the ECU that the vehicle has a certain speed. This will have a big influence of the steering performance of the car, since it is highly dependent on the vehicle speed. The reason why the dummy speed is introduced is that a very significant set of parameters, the boost curves, described above, are not available to be calibrated. The boost curves are affected indirectly via this parameter.

4.2.4 Calculating Calibration Values

In order to calculate new values for a curve, one has to make sure that the characteristics of the curve are still the same. This is to prevent an unrealistic behavior. The new curve is parametrized and calculated from a function and because of this, it is important to compare the calculated curve to the original one to make sure that they look alike. Many curves in the steering ECU share the characteristics with the following equation [6]:

$$y = a * x^b$$

Where a and b are varied in the design of experiment within reasonable limits, to make it similar to the original curve. The desired values of the curve are then picked out.

To ensure that the characteristics of the calculated curve match with the true curve in the ECU, comparisons have been made and can be seen in Figure 4.11.

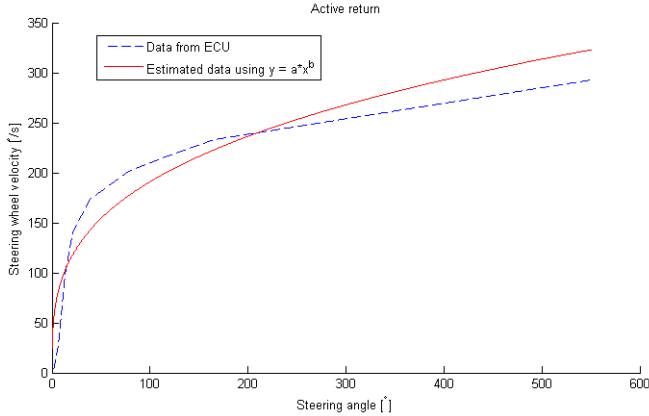


Figure 4.11: Active return [$^{\circ}/s$] as a function of steering wheel angle [$^{\circ}$]. The dashed red curve is the one found in the ECU and the solid blue curve represents an estimated curve based on the function $y = a * x^b$, for some parameter values a and b .

For the active return functionality of the car, there are five curves in the ECU that depend on longitudinal velocity of the car. In order to calibrate these, the method demonstrated in Figure 4.11 is used for calculating one of the curves and the other curves are calculated by multiplying this curve with a scaling factor. One of the five curves, the one used when the velocity of the car is zero, is not calibrated since the active return is always zero in this case.

4.3 Driving Maneuver Simulation

To be able to compare the performance between the Volvo steering model, the Pfeffer steering model and the steering rig, some kind of vehicle dynamics tests have to be done. To analyze the test results, objective metrics have to be used. Different tests require different metrics and the tests and metrics used in this work are defined in ISO-standards. The specific tests used in this work are the so called on-center tests, which are designed to test the steering "feel" and precision of a vehicle for high speeds but low lateral accelerations [14]. These tests are considered to be relevant for a proof of concept, since a car is mostly driven at high speeds and small steering wheel angles. Table 4.1 gives an overview of measured signals, target velocities and lateral accelerations for the different maneuvers.

Table 4.1: Table of target speed, lateral acceleration and which variables that are measured for each driving maneuver.

Maneuver	Target velocity (km/h)	Target lateral acceleration (g)	Variables to be measured
Weave test			Steering wheel angle Steering wheel torque Yaw velocity Longitudinal velocity Lateral acceleration Steering wheel angular velocity
Transition left	100	0.2	
Transition right			

4.3.1 On-center Handling – Weave Test

One of the tests used is the "on-center handling, weave-test", ISO 13674-1[15]. This is basically a test that while driving at 100 km/h, a sinusoidal input at the steering wheel is used with a fairly low frequency of 0.2 Hz. The maximum steering wheel angle should be around 15°, which corresponds to a lateral acceleration of 0.2 g in normal driving conditions. This test is of big interest since most of the time, a vehicle is driven straight forward with small steering wheel inputs [4]. Figure 4.12 shows the total input signal at the steering wheel during this test. One can see that the sinusoidal input is repeated for several periods which is important since the post-processing involves averaging of measured data.

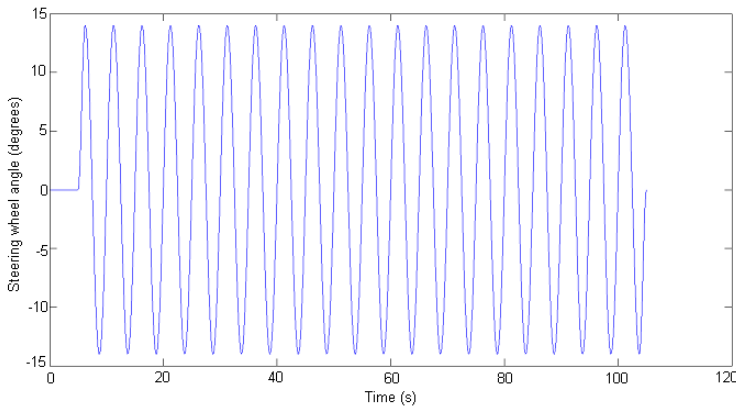


Figure 4.12: The input sinusoidal signal at steering wheel used in the weave-test.

The focus in this thesis work has been on the metrics related to steering wheel torque versus steering wheel angle, listed in the bulleted list below. For details of the calculation of these metrics used in this test, see Section 4.4.

- **Angle Hysteresis ($^{\circ}$):** Difference of steering wheel angle at zero torque between upper and lower part of hysteresis curve. This is a measure of how much the steering wheel angle differs from 0° when the steering wheel torque is 0 Nm .
- **Steering Friction (Nm):** Difference of torque at zero steering angle between upper and lower part of hysteresis curve. In other words, the friction of the steering wheel when driving straight forward.
- **Steering Stiffness (Nm/ $^{\circ}$):** Average gradient between steering wheel torque and steering wheel angle. This is in other words a metric that determines how much torque is needed to change the steering wheel angle. The gradient is averaged over the interval where the steering wheel angle is $\pm 1.5^{\circ}$.
- **Steering Stiffness at Zero Steer (Nm/ $^{\circ}$):** This is the same metric as "Steering stiffness" except for that it is calculated where the steering angel is $\pm 0.15^{\circ}$.

In order to give some feeling for the metrics, the calculated metrics are displayed in Figure 4.13 and 4.14. For a more detailed description on how the metrics are calculated, see Section 4.4.

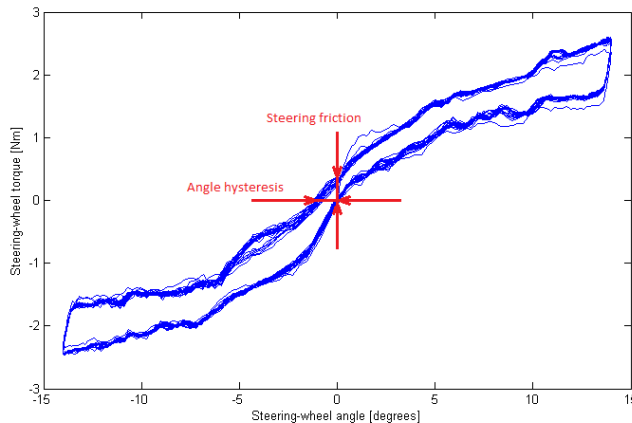


Figure 4.13: A visualization of the values that are taken from the steering wheel torque vs steering wheel angle plot. This figure shows the steering friction and angle hysteresis.

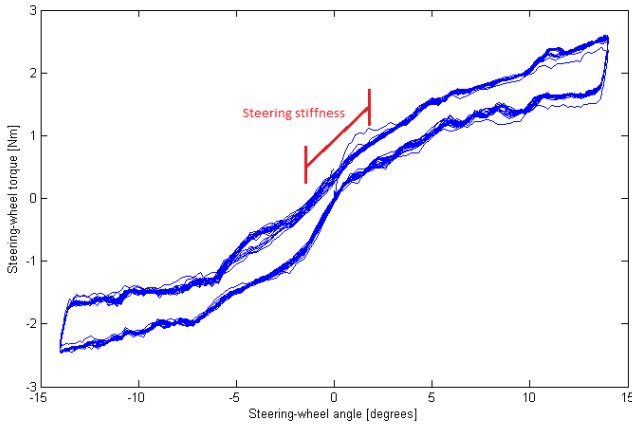


Figure 4.14: A visualization of the steering stiffness that is obtained from the steering wheel torque vs steering wheel angle plot. The steering stiffness is the gradient of the red line that goes between $\pm 1.5^\circ$ and is matching the data.

4.3.2 On-center Handling – Transition Test

Another test that was used was the "on-center, transition test", ISO 136741-2 [14]. The transition test examines the crossing from straight line running to the edge of the hysteresis loop. This test starts with driving at 100 km/h straight while ramping the steering wheel angle. This should be done, until the lateral acceleration reaches at least 1.5 m/s^2 , as specified in the test.

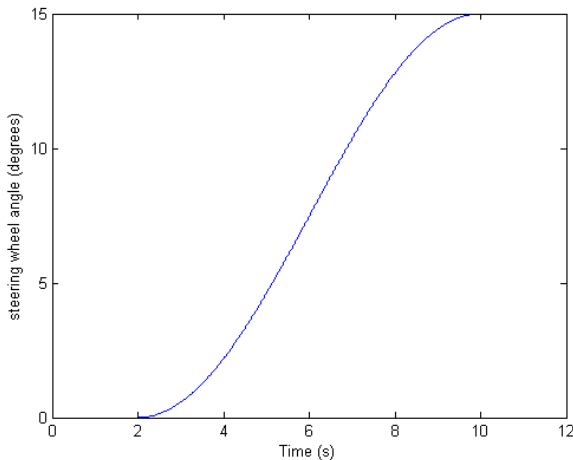


Figure 4.15: The ramping input signal at the steering wheel used in the transition test.

The metric related to steering wheel torque versus steering wheel angle in this test is steering stiffness. Figure 4.16 shows how this looks.

Steering Stiffness ($\text{Nm}/^\circ$): Gradient of straight line fit to the linear part of the data to determine how much torque is needed to change the steering wheel angle.

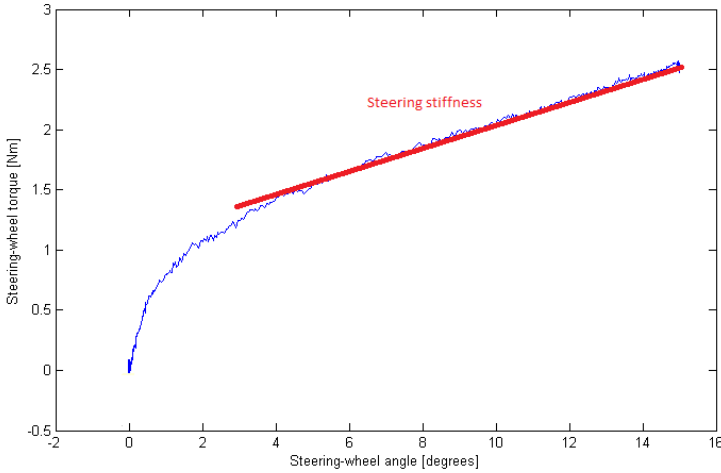


Figure 4.16: The steering stiffness metric is the gradient of the straight line matched to the measured curve. Only the linear part of the curve is of interest in this test.

4.4 Post-processing

The post-processing of data is an important part of the automated process and evaluates how good the performance of the steering system is for a given set of parameter values.

The post-processing takes measured samples from a testrun as input and returns metrics describing the steering performance as output. Examples of inputs to the post-processing are vehicle speed, steering wheel torque and tie rod forces. The metrics are calculated in a certain way, specified by the specific ISO standard in which the evaluated test case is defined; that is, different test scenarios require different post-processing metrics. The ISO standards used in this thesis work are the ISO 13674-1 and ISO 13674-2 which are described in Section 4.3.1 and 4.3.2.

4.4.1 Weave Test

The weave-test has been performed in HIL and the steps of post-processing are described in this section.

The result plot of steering wheel torque versus steering wheel angle characteristi-

cally has the form of a hysteresis loop, as can be seen in Figure 4.17. The first step in the post-processing for the weave-test is to sort out 60% of the values that are inmost in steering wheel angle by cutting off 20% of the upper and lower angle values. This is done according to the ISO-specifications.

The next step in the process of the post-processing is to decide whether a sample is within the upper or lower part of the hysteresis curve. This is done by sorting out the samples depending on if their steering wheel velocity is positive or negative and the result can be seen in Figure 4.18. The last step in the post-processing is to estimate two curves that fit the data, so that the metrics can be measured in a simple manner. The curve-fitting is done with a third order polynomial using the Matlab function `polyfit`. With this data, it is now possible to calculate the metrics mentioned in Section 4.3.1.

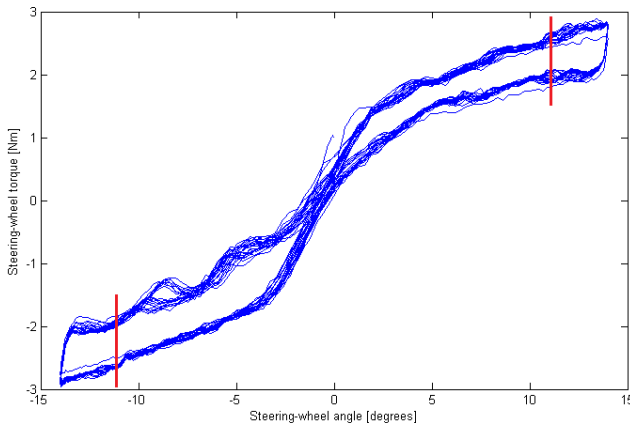


Figure 4.17: The hysteresis curve that steering wheel torque versus steering wheel angle generates in this test. The red lines mark where the cutting is done.

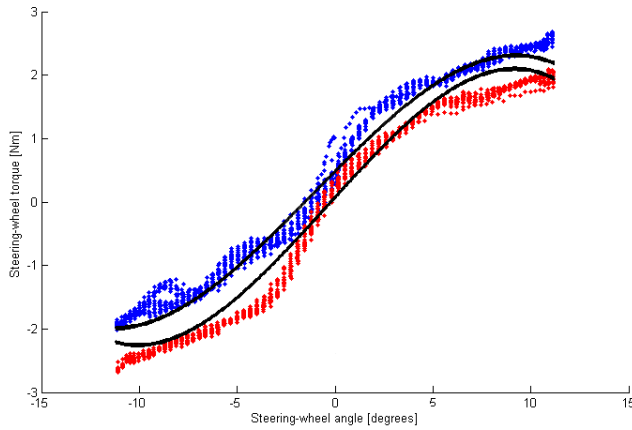


Figure 4.18: The hysteresis curve after sorting out negative and positive steering wheel velocity. Blue represents positive velocity and red is negative velocity. The black lines represents the polynomial fit of degree 3.

4.4.2 Transition Test

The result plot of steering wheel torque versus steering wheel angle looks characteristically as in Figure 4.19.

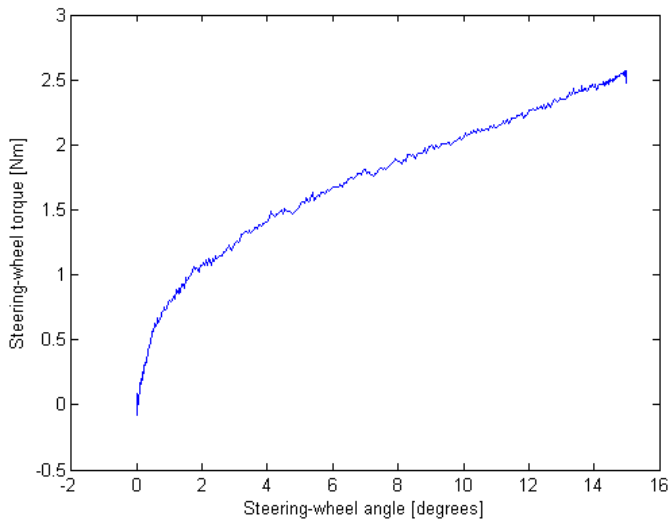


Figure 4.19: The resulting steering wheel torque versus steering wheel angle in the transition test. This figure is from a HIL simulation of a left turn.

First the non-linear part of the data is cut off. This is done by cutting off the values for steering wheel angles smaller than 3° . The last step is to fit a straight line to the data that is left. The steering stiffness is then the gradient of this line. Figure 4.20 shows the corresponding figure with both post-processing steps.

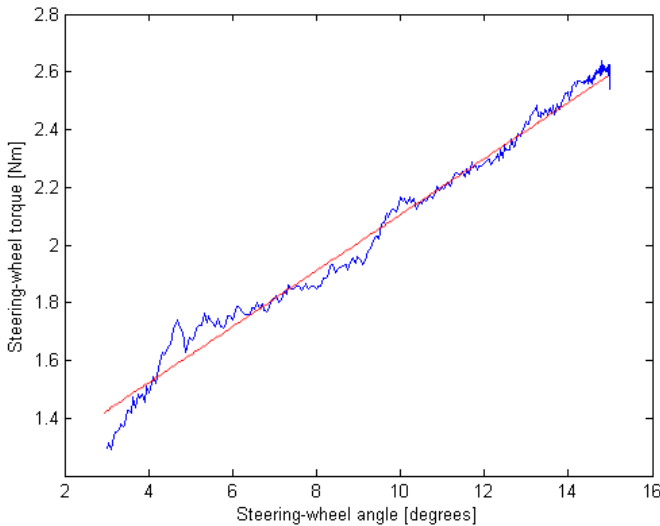


Figure 4.20: Postprocessed data from a left turn in the transition test. The straight line that matches the postprocessed data of a left transition-test best. The gradient of this line is the steering stiffness-metric.

4.5 ModeFrontier

The workflow in the program ModeFrontier, the program that controls all programs connected to the laptop and PC, is illustrated in Figure 4.21. In order to design a test sequence, a design of experiment (DoE) is constructed. The DoE uses the calibration parameters a , b , $drvMod$ and $dummyspeed$, and decides which parameter configurations to test. a and b are used in the Matlab script to get a full curve for the active return function. Then five values from the curve are taken out and used to calibrate a simplified curve in INCA, this is done via a Visual Basic-script. After that a CarMaker simulation is run by a Python-script over a TCP/IP connection that connects the laptop to the PC via a twisted pair cable. Two parameters are set in the CAN-simulation via CarMaker: a dummy speed and a drive mode that both goes to the ECU. The result is then saved in a shared folder where a Matlab-script on the laptop post-processes the data from the simulation. Eventually the DoE changes the variables a , b , $drvMod$ and $dummyspeed$ and repeats the experiment.

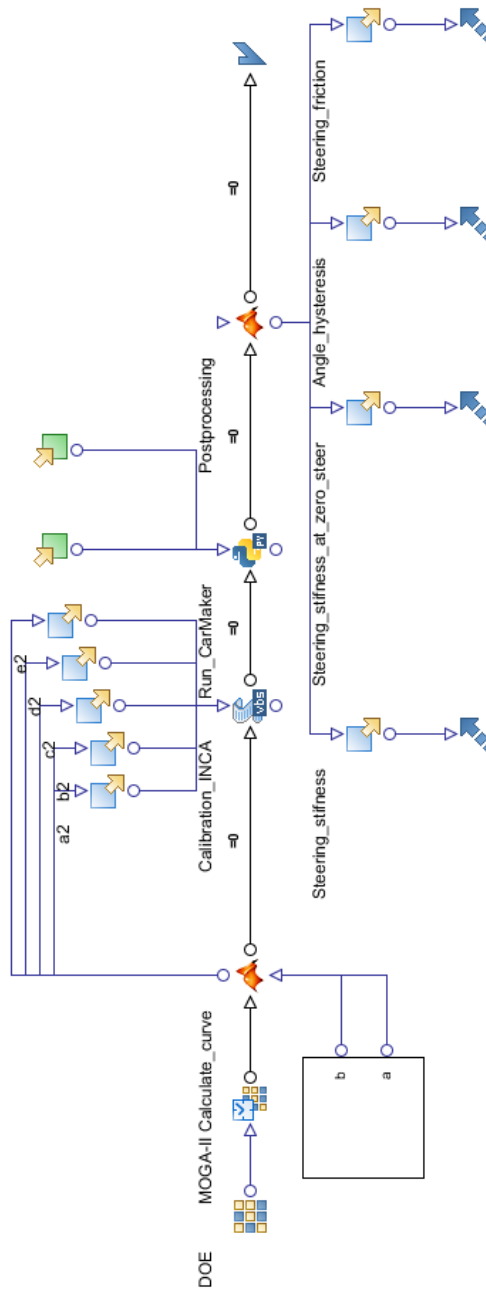


Figure 4.21: The experiment setup in ModeFrontier.

5

Results

One of the main tasks in this thesis work was to validate the steering system, both in HIL and SIL. One part of the validations was to compare Pfeffer's versus Volvo's steering model in SIL and another part was to compare HIL versus SIL with Volvo's steering model. The validations were performed by simulating a couple of driving scenarios on the different steering system configurations. The results were analyzed both by comparing plotted values but also by comparing calculated metrics. The driving maneuvers and metrics used for the comparison were described earlier in Section 4.3.

A comparison between different steering gears was also performed and is presented and discussed in this chapter.

Another important task was to run HIL simulations for different parameter values to investigate how a certain parameter or combination of parameters affect the outcome of the test. The same driving scenarios and post processing methods as for the validations were used.

5.1 Results for Simulations Without Calibration

This section contains all validations performed on the SIL and the HIL configurations and are done with standard settings delivered by the supplier of the model. This means that the standard settings *drvMod* is set to medium and no *dummyspeed* is used, so the actual vehicle speed is used.

5.1.1 Pfeffer Steering Model vs Volvo's Steering Model in SIL

To compare the Pfeffer steering model with Volvo's steering model, the two models were tested with the on-center, mentioned in Section 4.3.1 and 4.3.2. The

results from the tests were post-processed and are presented in Figure 5.1-5.2, and Table 5.1-5.2. The models are not exactly the same and therefore it is expected to get small differences in the tests. The small differences that occur will however have minimal impact, if any at all.

Weave Test

The comparison between the parameterized Pfeffer steering model and Volvo's steering model shows that they are very similar. The hysteresis curves are on top of each other, which can be seen in Figure 5.1. The resulting metrics for both steering models are summarized in Table 5.1 and it is clear that the differences are very small.

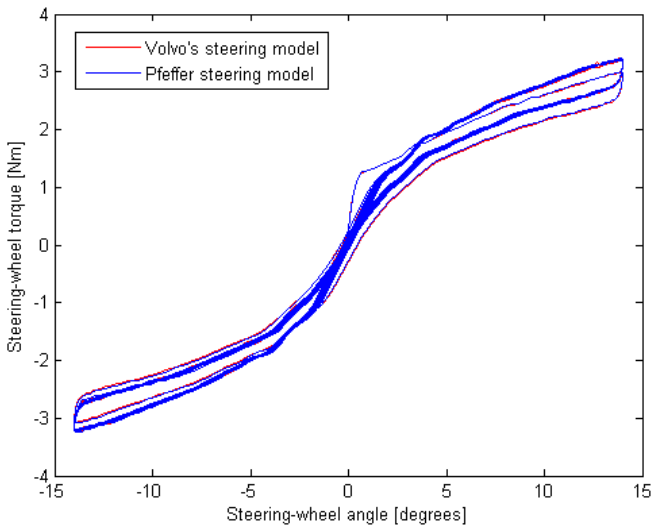


Figure 5.1: Hysteresis curve of the SIL models for the weave test.

Table 5.1: The resulting metrics from the weave test for Volvo's steering model and the parameterized Pfeffer model.

Metric	Volvo's steering model	Parameterized Pfeffer model
Angle hysteresis (°)	0.6400	0.6300
Steering friction (Nm)	0.2613	0.2558
Steering stiffness (Nm/°)	0.3969	0.3971
Steering stiffness at zero steer (Nm/°)	0.4043	0.4045

Transition Test

The results from the simulations of the different models in the transition test are very similar, both in the plot and the metrics, which can be seen in Figure 5.2 and Table 5.2 respectively.

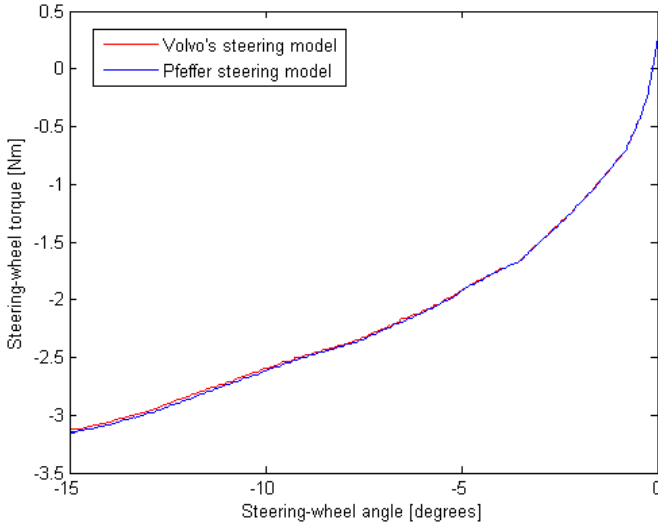


Figure 5.2: The resulting steering wheel torque versus steering wheel angle for the SIL models in the transition test left turn. The results matches each other very well.

Table 5.2: The resulting metrics from the transition test for Volvo's steering model and the parameterized Pfeffer model.

Metric	Volvo's steering model	Parameterized Pfeffer model
Steering stiffness (left turn) (Nm/°)	0.1193	0.1209
Steering stiffness (right turn) (Nm/°)	0.1209	0.1220

5.1.2 HIL vs SIL

Comparisons were performed between HIL and SIL in order to see what the differences and similarities are and to be able to investigate where they occur from. The comparisons were performed by evaluating the same tests, with the same vehicle maneuvers in both HIL and SIL. The tests performed were the weave test and the transition test, described in Sections 4.3.1 and 4.3.2 respectively. The test results were then post-processed in order to calculate the metrics corresponding

to each test. The raw sample data was also plotted in order to get a better understanding of the behavior of the steering system.

Weave Test

The results from the HIL- and SIL-simulations for the weave test are presented in Figure 5.3, where the hysteresis is plotted and in Table 5.3, where the objective metrics are summarized.

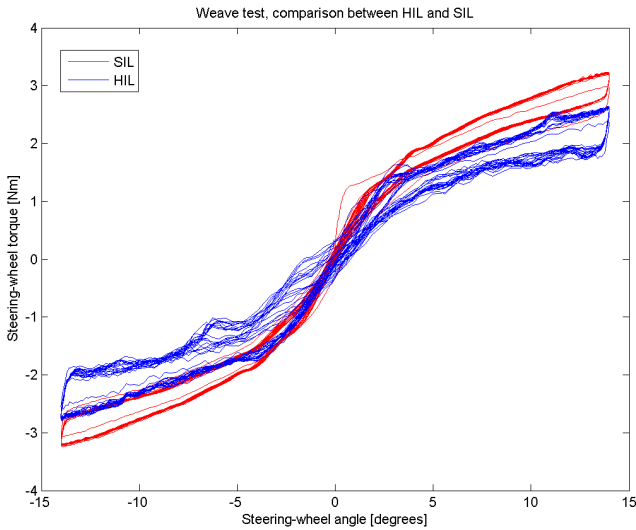


Figure 5.3: Comparison between hysteresis curves from a weave test performed on HIL (blue curve) and SIL (red curve).

Table 5.3: The resulting metrics from the weave test for the HIL- and SIL-simulation with Volvo's steering model.

Metric	HIL	SIL
Angle hysteresis (°)	1.48	0.6400
Steering friction (Nm)	0.4027	0.2613
Steering stiffness(Nm/°)	0.2643	0.3969
Steering stiffness at zero steer (Nm/°)	0.2687	0.4043

The first observation that can be made is that the measurements from the HIL simulation are noisier and more fluctuating than the measurements from the SIL simulation. The reason why the hysteresis curve from the HIL simulation is noisier than the one from SIL is that the HIL simulation uses real hardware sensors to acquire desired measurements. The main reason why the hysteresis curve from

HIL is more fluctuating than the one in SIL is that the friction in the steering gear is not constant in HIL and will therefore vary.

Another important thing to note is that the plots for the HIL and SIL simulations both have the characteristic hysteresis appearance. The curve representing the HIL-simulation looks a little bit flattened compared to the one representing the SIL-simulation. This results in the absolute value of the maximum and minimum steering wheel torque being approximately 15% smaller in the HIL case. The reason for this is that the SIL model does not accurately describe the friction of the steering gear and that friction varies between different steering gears, which is discussed in Section 5.1.3. Another result is that the gradient of the curve is smaller in the HIL case. This means that less torque is required to move the steering wheel the same number of degrees in HIL compared to SIL. This is confirmed by the steering stiffness metric in Table 5.3, where the steering stiffness for HIL is about 33% lower.

Transition Test

The results from the HIL and SIL simulations for the transition test with left turn is presented in Figure 5.4 where the steering wheel torque is plotted against the steering wheel angle and in Table 5.4 where the objective metrics are summarized.

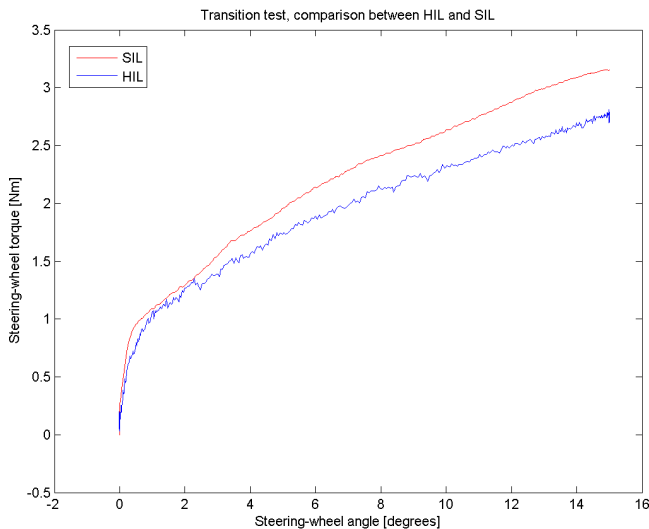


Figure 5.4: Comparison between plots of steering wheel torque versus steering wheel angle from a transition test performed on HIL (blue curve) and SIL (red curve) for a left turn.

Table 5.4: The resulting metrics from the transition test for the HIL- and SIL-simulation with Volvo's steering model.

Metric	HIL	SIL
Steering stiffness (left turn) (Nm/°)	0.1037	0.1193
Steering stiffness (right turn) (Nm/°)	0.1060	0.1209

The same conclusions about the fluctuating and noisy behavior in HIL can be drawn from the discussion in the section for the weave test above.

The steering stiffness is about 15% lower for the HIL than for the SIL. This is mainly because of difficulties with modeling the friction of the steering gear; the friction of the steering gear is discussed further in Section 5.1.3.

5.1.3 Different Steering Gears in HIL

The difference in performance for simulations in HIL occur due to several reasons and those are discussed in this subsection, where also simulation results are presented.

The difference between a left and a right turn in the transition test is shown in Figure 5.5. They are mirrored and besides that, they look characteristically the same. The fact that the both plots are symmetric, besides the mirroring, means that a transition test for a right turn guarantees that there is no significant offset in angle for the steering rig.

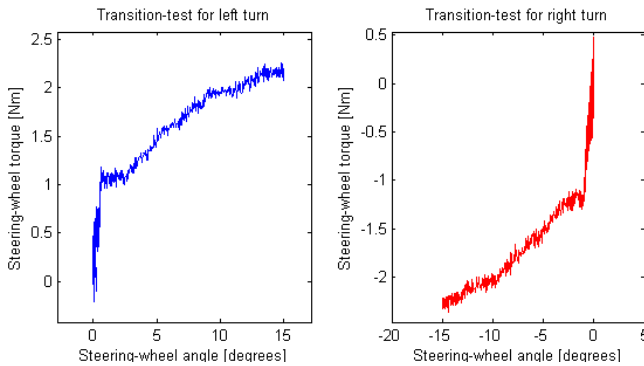


Figure 5.5: The difference between a left and a right turn in the transition test simulated in HIL.

One of the main reasons differences in performance for different steering gears occur is because of the physical components of the steering gear. The properties change, mainly depending on the amount of wear the steering gear has been exposed to; this will for example affect the friction of the steering gear, since an old and worn steering gear will have less friction than a new one. This will result in

that less force is needed to move the steering rack of a used steering gear than the one of an unused. Other physical differences and imperfections will of course also influence the performance of the steering gears.

In Figure 5.6, test results for the weave test from HIL simulations with a newer and a worn steering gear is plotted. Notice that the worn steering gear (red curve) has lower steering wheel torque. Since the worn steering gear has less friction than the newer steering gear (blue curve), less torque is needed to make the same maneuver, as concluded above. It may seem like the red curve is noisier than the blue one but it is not. It looks like this because the red curve is plotted on top of the blue one.

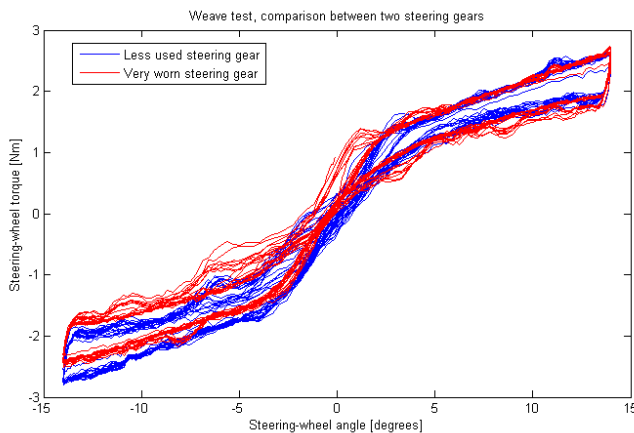


Figure 5.6: The figure shows two hysteresis curves that are obtained when running a weave test on the steering rig with two different steering gears.

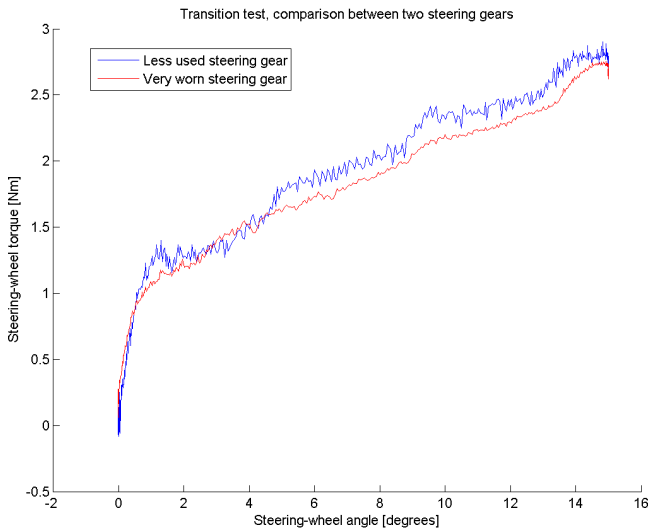


Figure 5.7: The figure shows two curves that are obtained when running a transition test on the steering rig with two different steering gears.

The same conclusion as above can also be drawn when looking at Figure 5.7. Here two curves are plotted for two different steering gears in HIL for the transition test with left turn. The worn steering gear (red curve) has lower steering wheel torque in general, since the worn steering gear has less friction than the newer steering gear (blue curve) and therefore less torque is needed to make the same maneuver. The newer steering gear has lower friction around 2-5° and this has to do with the variation in friction for each steering gear. If the frictions of the steering gears was constant, this behavior would not be present.

5.2 Different Parameter Configurations in HIL

This section investigates how certain ECU parameters affect the test results for on-center tests in HIL. Numerous tests are performed from the automated process in ModeFrontier, described in Chapter 4. This means that new ECU parameters are calibrated before each test is performed and after the test is performed, the metrics are calculated. The ECU parameters and the metrics are then analyzed in order to see trends and correlations between them. A discussion about the results is then held in order to explain the different phenomena.

When looking into performance differences between different steering gears it is very important to consider the software and parameters in the ECU which highly contribute to the performance of the steering system. An example of an important parameter is the driving mode, *drvMod*, which was mentioned in Section 4.2.3. A comparison between two HIL simulations, with different driving

modes can be seen in Figure 5.8. It is clear that when driving mode is high, the servo applies less assisted force and therefore the steering wheel torque needs to be higher, in order to perform the same maneuver as when the driving mode is low.

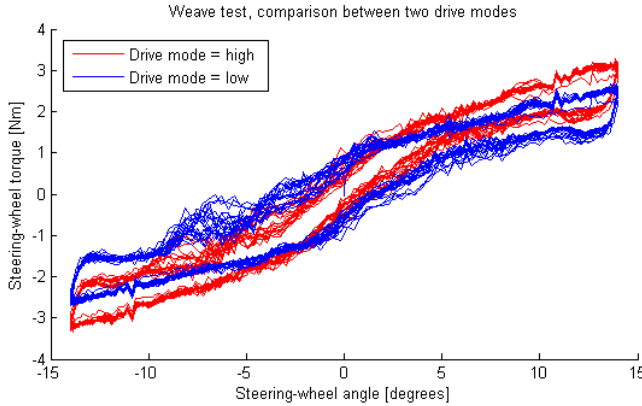


Figure 5.8: The figure shows two hysteresis curves that are obtained when running a weave test on the steering rig with two different driving modes activated; the red curve represents $drvMod = high$ and the blue curve represents $drvMod = low$.

5.2.1 Weave Test

For the weave test, an experiment of 76 simulations was performed. The SOBOL algorithm [16], which uniformly samples the design space, was used to construct the DoE for these tests.

The charts in Figure 5.9-5.12, show the effect each input parameter has on the objective metrics. A direct effect means that an increase in a parameter yields an increase in the metric. An inverse effect means that an increase in a parameter yields a decrease in the metric. Figure 5.9 shows that an increase in all calibration parameters result in a decrease in the angle hysteresis. The parameter that affects this metric the most is the *dummyspeed* parameter and the parameter that affects it second most is *b*, which affects it significantly less. The inverse effect of *dummyspeed* on angle hysteresis can be explained by the fact that less disturbance and less influence of a small angle is desired when driving at higher speeds.

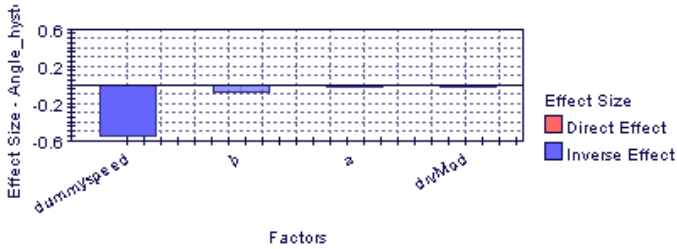


Figure 5.9: Effect on the angle hysteresis metric for each calibration parameter for the weave test.

The effect on the steering friction metric reminds of the effect on angle hysteresis. The difference is that the *dummySpeed* parameter has a smaller negative influence on the steering friction. This means that the steering friction decreases less than the angle hysteresis when *dummySpeed* is increased, as can be seen in Figure 5.10. The same explanation as for the angle hysteresis can be applied here, at higher speeds, the steering wheel is less sensitive.

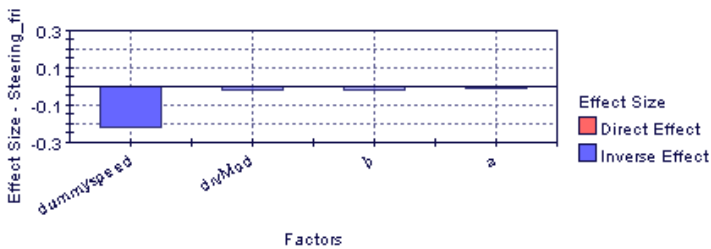


Figure 5.10: Effect on the steering friction metric for each calibration parameter for the weave test.

The steering stiffness and steering stiffness at zero steer are affected in a similar way by the parameters, which is expected since the two metrics are very similar.

There is a direct effect on the metrics steering stiffness and steering stiffness at zero steer when increasing all parameters individually, this is shown in Figure 5.11 and 5.12. This is expected, since it is desirable for the steering to react less aggressive when driving at higher speeds. This means that more torque needs to be applied on the steering wheel in order to change the steering angle. An increase in *a* and *b* result in a higher active return, which means that more applied torque is required to do the steering. This is because the active return-function applies a torque opposite to the steering wheel torque, in order to return the steering wheel angle to 0° .

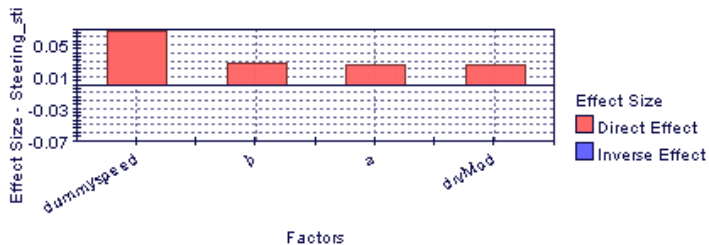


Figure 5.11: Effect on the steering stiffness metric for each calibration parameter for the weave test.

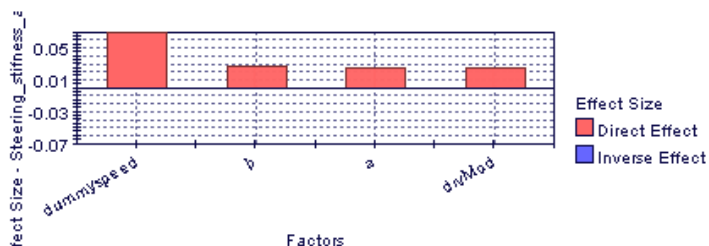


Figure 5.12: Effect on the steering stiffness at zero steer metric for each calibration parameter for the weave test.

To summarize the results of the weave tests, a correlation matrix is presented in Figure 5.13. Each column shows the same as the charts, but what is also seen is how directly each parameter is connected to the metrics. The *dummyspeed* parameter is dominant in affecting all metrics.

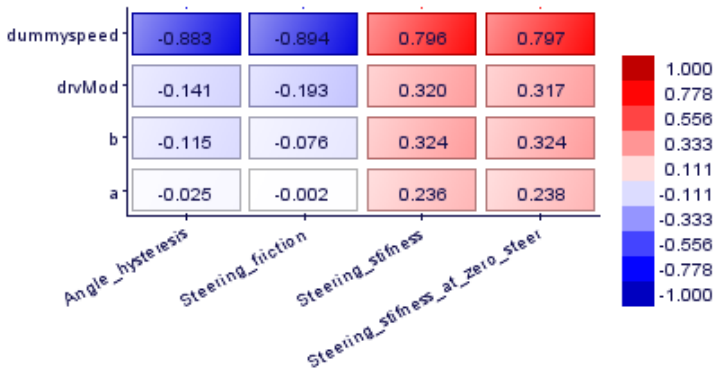


Figure 5.13: Correlation matrix of the calibration parameters and the objective metrics for the weave test.

5.2.2 Transition Test

The DoE for the transition test was carried out as a full factorial DoE with the outliers for all parameters except for *drvMod*, where all three modes were used. This resulted in 24 simulations.

The steering stiffness metric in Figure 5.14 shows a different behavior for the transition test compared to the weave test. All parameters affect the steering stiffness less for the weave test and this is expected since the value in general is lower; compare Table 5.4 and 5.3.

Another difference is that the parameters *a* and *b* have an inverse effect on steering stiffness in the transition test. There are several possibilities why this phenomena occurs but the main reason is that in the transition test, there is no turning back of the steering wheel towards its neutral position 0° . This will result in less active return torque, since the active return functionality is mainly activated when turning the steering wheel back towards 0° .

The *drvMod* and the steering stiffness are inversely correlated but the correlation is very low. One reason for this is that the turns are for low steering wheel angles and it is therefore difficult to notice any difference at all for different driving modes.

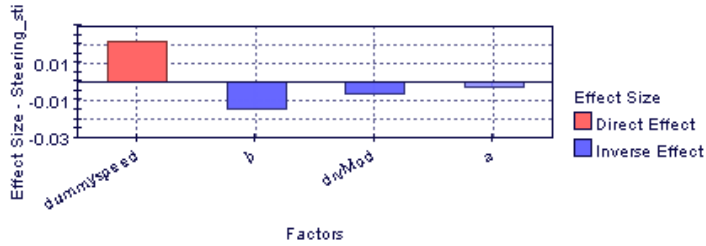


Figure 5.14: Effect on the steering stiffness metric for each calibration parameter for the transition test.

The correlation between the four input parameters and steering stiffness for the transition test is shown in Figure 5.15. *Dummyspeed* is very tightly coupled to the steering stiffness.

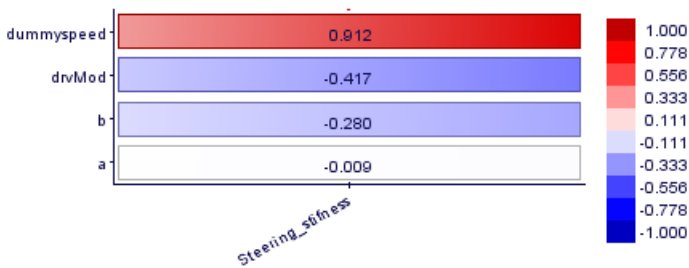


Figure 5.15: Correlation matrix of the calibration parameters and the steering friction for the transition test.

6

Conclusions and Further Work

The goal of this thesis work was to show that this method of calibration, simulation, and analysis in a HIL rig could be used as a tool to acquire relevant information about the steering system and also to get desired performance. These ideas have been successfully realized, and have generated a method to analyze, calibrate and simulate steering systems for passenger cars.

The different simulation results discussed in Chapter 5 indicate that there are several factors affecting the steering system's behavior. It is important to remember that a perfect match in results after simulations in HIL and SIL should not be expected. Simulations in HIL and SIL will naturally differ from each other since a SIL is a modelled HIL and a model never describes the reality exactly. Differences between different simulations in HIL are also to be expected since friction differs depending on wear. In this case it is of more importance to understand why the differences occur and also to limit them to get more continuous test results, rather than trying to eliminate them.

Since this thesis work was focused on a proof of concept, it is natural to continue working on this project by developing a way to optimize the calibration of the ECU parameters of the steering gear. This will make it possible to configure the ECU parameters in order to achieve desired performance from the steering system. This was not possible in this thesis work due to the lack of calibration parameters to calibrate. Work has been done in this field but in SIL, with good results [6, 17].

The future optimization of ECU parameters can be done in ModeFrontier which has a variety of optimization tools and analysis methods. By doing this, the desired performance of the steering gear can be achieved roughly in HIL, before the steering gear is installed in a car. This will shorten development time of steer-

ing gears tremendously, since the ECU parameters will hopefully only need to be slightly adjusted when the steering gear is installed in the the car.

Another interesting thing would be to investigate which properties are better suited to be tested and verified using simulations in SIL and HIL respectively. Some parameters might only be possible to calibrated in a test vehicle. There are for example naturally some tests that cannot be run in the steering rig since the applied tie rod forces are limited to only act in the y-axis direction. Some driving maneuvers may for example include tie rod forces in the x- and z-axis direction as well.

It would be very useful to verify and parameterize SIL models by doing simulations in HIL. For example a better understanding of the steering gear might yield a better modeling of the friction in the SIL model.

In order to be able to use the method presented in this thesis work efficiently, a good way to correlate the objective metrics to subjective steering feel is needed. This is a field where research has been going on for decades and it is certainly a possible path to follow after this thesis work.

Appendix

A

Picture of the Rig

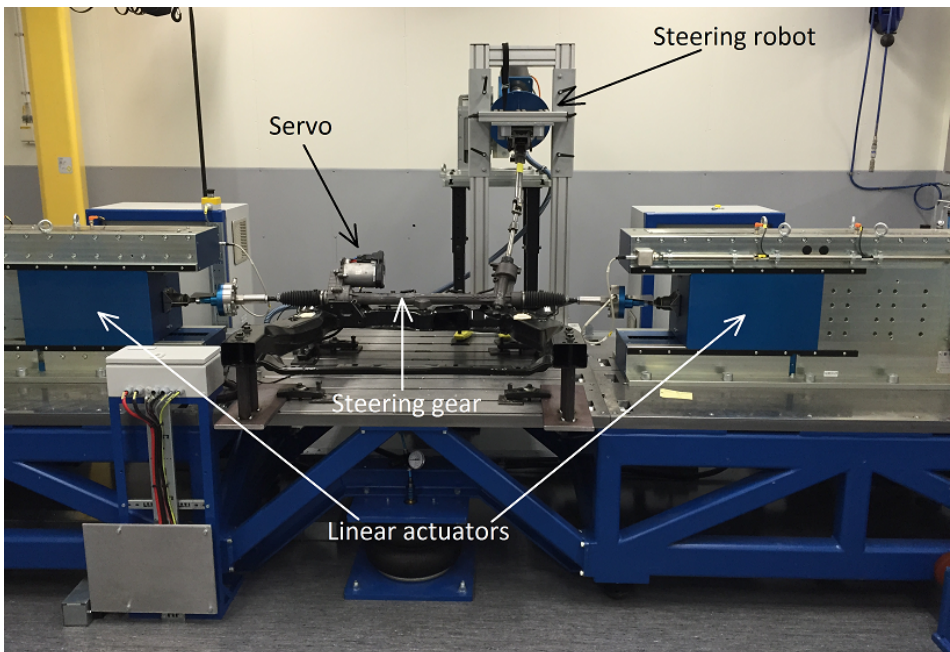


Figure A.1: The rig used in the thesis work. A subframe is mounted in front of the steering gear.

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